Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 71 (1994)

Rubrik: Session 3: Managing crowds and hazard scenarios

SESSION 3

MANAGING CROWDS AND HAZARD SCENARIOS

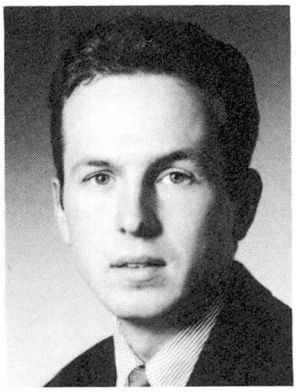
Leere Seite
Blank page
Page vide

Crowd Behaviour and Associated Management

Comportement et contrôle des mouvements de foule

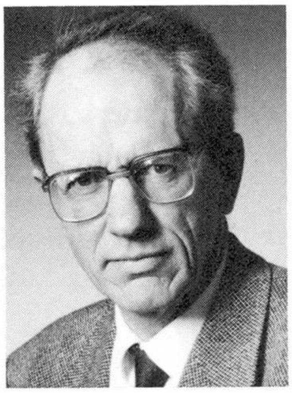
Verhalten und Kontrolle von Menschenmassen

Graham WANLESS
Graduate Engineer
Maunsell & Partners
Beckenham, UK



Graham Wanless, born in 1969, graduated from Manchester Univ. with a first class B. Engineer (Hons) degree in Civil Engineering in 1990, and an M.Sc entitled "Crowd Safety" in Spring 1992. Since this time he worked as a graduate engineer for G. Maunsell & Partners.

Richard STANTON
Senior Engineer
Maunsell & Partners
Beckenham, UK



Richard Stanton, born in 1938, graduated from Imperial College, London Univ. with a B.Sc. (Eng.) in 1959. He is a European Engineer and has studied transport planning in all its forms, since joining G. Maunsell & Partners after graduation.

SUMMARY

The behaviour of a crowd will influence the way in which it is managed. This paper discusses factors which affect this behaviour and the techniques which must be implemented to cope successfully with crowds. A wide variety of events and activities have been cited throughout, in order to demonstrate a number of possible crowding scenarios.

RÉSUMÉ

Le comportement des foules influence le mode de contrôle à utiliser. Les auteurs exposent les facteurs actifs et les techniques à prévoir pour agir sur les mouvements de foule. Ils mentionnent un grand nombre d'événements et d'activités, et présentent une série de comportements possibles d'une masse humaine.

ZUSAMMENFASSUNG

Das Verhalten von Menschenmassen beeinflusst die Art ihrer Kontrolle. Der Beitrag diskutiert die wirksamen Faktoren und die anzuwendenden Techniken, um erfolgreich mit Menschenmassen umzugehen. Es wird auf eine Vielzahl von Ereignissen und Aktivitäten bezug genommen, um eine Reihe möglicher Verhaltensweisen von Menschenmassen zu demonstrieren.

1. INTRODUCTION

Crowds are a common occurrence. Each and every crowd will exhibit certain characteristics which depend upon the individual set of circumstances surrounding them. People attending a political rally or demonstration will act in a totally different manner to those leaving an operatic performance. It is not only the event which causes these differences; structural, physical and psychological aspects such as the facility design, patron mobility and personal expectation all influence the way in which the crowd will behave.

Crowds should be managed wherever possible. A facility, which has met the necessary requirements in terms of physical structure, may still provide an unacceptable level of crowd safety, if the operations team to complement it do not manage the crowd effectively. A crowd management plan should be created using a systematic approach. The way in which a crowd is managed will depend upon its components and characteristics. The management strategies created must be flexible so they can be adapted to fit the crowd. All possible factors which can influence a situation must be considered so that it can be managed safely. Critical levels of crowd density and triggering of rapid group movement must be avoided. Failure to achieve these basic requirements can result in serious incidents.

Throughout time there have been numerous crowd related incidents, both portents and fully blown tragedies. Although the overall safety of public places has increased, disasters which emanate from a small number of causes still arise. These causes can manifest themselves in emergency and normal situations (ingress and egress), by standing pressure and structural failure. Each individual crowd disaster has its own set of circumstances.

2. CROWD BEHAVIOUR

2.1 Movement

Crowd movement will exhibit different characteristics, depending upon the particular circumstances involved. Normal movement is encountered everyday in a variety of locations. Members of this type of crowd may or may not have a common objective. It may be uni- or multi-directional, move at different speeds and occur within a wide range of densities. Examples of this type of flow include strolling, window shopping, passage through a railway or underground station with crossing flows, movement into, within and out of public places such as airports, theatres, cinemas and stadia. In contrast, people in an emergency do have a common objective. This is to either enter or leave a certain area as a consequence of an action, such as an outbreak of fire or a bomb-scare. Emergency movement is not necessarily survival of the fittest; people often move in small units, for example, families.

2.2 Crowd Types

One tends to think of a crowd as having one particular personality or set of traits. This could range from a relatively calm crowd leaving a theatre, to a dense and expressive crowd at a pop concert. However, this is too simplistic. Each crowd will be made up from a number of sub-groups. Some of these groups may dominate others but differences will exist. One such group, which must not be ignored, are those with disabilities or restricted movement. These people, may be expected to be present in all types of crowd. Spectators are another type of crowd, which in turn will have sub-groups of its own. Different parts of the crowd could be passive, active, dancing or celebrating. Equally, part of a protesting crowd could comprise peaceful, calm, aggressive, hostile or even violent people.

2.3 Group Characteristics

The type of crowd refers to its physical composition and action. Crowd characteristics on the other hand are more to do with the state of mind. A commuter will act in a totally different way to a tourist whilst travelling by underground. The commuter is very positive in his or her actions. They will know precisely where they want to go, by which route and which platform. Their timing will often be calculated to optimise their travelling time. By contrast, the tourist needs guidance and instruction to use the same system effectively.

Some people lose their inhibitions, when in an aroused crowd, and find themselves doing things they would not normally allow themselves to do. This action could be in the form of shouting abusive material or becoming aggressive. There are numerous other crowd characteristics, which can be fuelled by emotion and desire. These can lead to a crowd exhibiting a certain degree of organisation, leadership or bonding. The characteristics are by no means exclusive to one type of crowd, or to each other. Every crowd will be different.

2.4 Building Types and Their Facilities

The potential for crowd build-up is not only apparent in locations termed "places of assembly". People can congregate away from these areas for activities such as shopping, demonstrations and fire-drills. Structures where crowd behaviour is an important consideration include offices, theatres, cinemas, public houses, night-clubs, concert halls, shopping malls, sports grounds, exhibition halls, railway stations and airports.

The suitability of a structure to cope with crowds will depend upon the patronage. Take the example of an underground station during an emergency evacuation, where there may be significant proportion of disabled or infirm people. The physical nature of underground stations mean that some will be more suited to dealing with this type of crowd than others. The facilities within a structure are also an important consideration when looking at crowd behaviour. Ease of passage should be ensured for all patrons in both the normal and emergency situation. Passageways, lifts, stairs and escalators should all interact where they occur. There should be sufficient facilities within a structure to ensure that the crowd can be effectively managed. Where this is not the case, it is possible for the mood of the crowd to alter. People can become frustrated, irritated and impatient if things do not run smoothly. Situations where crowd mood changes can be termed triggers.

2.5 Triggers

Certain events can influence or even alter the behaviour of a crowd. These can be grouped into three main categories: physical, natural and human. Physical influences can be defined as structural or service based. Structural failure, the temporary closure of pedestrian routes, restricted viewing of an event and the cancellation or inadequacy of a service all fall into this category. Excessive heat, humidity, rain, hail, earthquakes, flooding and fire are all natural effects. An example of a human effect is that it will react to the way it is managed or controlled. Confusion can occur if the crowd is not fed sufficient information to cope with its needs. A crowd can also be incited by gestures, whether it be by a performer or somebody managing them.

3. ASSOCIATED MANAGEMENT

3.1 Crowd Management and Control

The terms crowd management and crowd control are often misused. They are frequently mistaken to mean the same thing. The basic distinction between the two titles are the words management and control. The former is an active action, whereas the latter is reactive. Crowd management covers all actions taken (planning, supervision, monitoring the movement of people, provision of adequate refreshments and lavatories etc) to ensure the smooth running of an operation. The aim is to provide a pleasurable experience for the patron. The operation itself could be anything from the Harrods Sale to New Year celebrations in Trafalgar Square.

Once the potential crowd types and characteristics have been identified, the operations manager should create a crowd management plan which covers all foreseeable scenarios. The plan should take the form of a systems approach (as opposed to piecemeal), which links all aspects together. This task will be more difficult for a manager of a multi-purpose arena than, say, a theatre. The former might have to effectively manage a rap-concert and a boat show within the same physical structure. Following completion of the crowd management plan it should be reviewed at regular intervals to examine whether or not it is working effectively. Between reviews, crowd behaviour and operational experience should be monitored. Revisions can therefore be made from actual events.

A useful tool for crowd management has been developed by Fruin [1]. He has created a model to aid understanding of crowd disaster causes, means of prevention and possible mitigation of an ongoing incident. The model is called "*FIST*", which stands for *Force* (of the crowd; pressure), *Information* (upon which the crowd reacts whether it be real, perceived, true or false) *Space* (involved in the incident; physical facilities) and *Time* (duration of the incident; scheduling; processing rate).

Crowd control is a reaction to a situation, which is not desirable. Measures of this type should ideally form part of the overall crowd management plan. However it is recognised that unforeseen circumstances do occur; in which case there could be a previously unplanned reaction to a problem. Crowd control should only be used as a last resort. It is far better to guide a situation, rather than oppose it with force. The aim is to revert to a policy of crowd management as soon as possible, with the minimum of disruption. Measures used in crowd control could include arrest, the use of force if necessary and the blocking of certain entrances and exits to alter the patterns of occupancy and movement. It should be noted that control procedures can dramatically increase the severity of a crowd incident if the adopted action is inappropriate. An example of such an incident is the crowd disaster which occurred in Lima, Peru in 1964, which claimed 318 lives [2].

3.2 Communications

The link, which is often missing in crowd management, is that of communication. Each member of a crowd will make decisions based upon the information they have to hand. A lack of information can lead to people making assumptions, which may not necessarily be correct. A clear example of this occurred the day New York's Brooklyn Bridge opened. A scream was interpreted by members of the crowd in such a way that they thought the bridge was about to collapse. As a consequence, 12 people were killed and a further 27 seriously injured, in the apparent emergency egress [3].

In many crowd incidents there has been a distinct lack of communication between people located at the heart of the problem and those elsewhere, who unwittingly contribute to the problem. An example of this is where someone has fallen on a stairway and people further up carry on moving down the stair. This is often termed a lack of front to back communication. Crowd disasters at Bethnal Green Tube Station (1943), Ibrox (1971) and Hillsborough (1991) all exhibit this deficiency. Detailed case studies of these disasters have been presented in [2].

3.3 Evacuation

With regard to crowd management, an important aspect of emergency movement is the evacuation of patrons and staff. This should be documented within the crowd management plan. It should be remembered that, in the event of a fire (or other cause), certain escape routes might be blocked. Wherever possible, evacuation plans should reflect this.

Different ways of communicating with the public will result in different responses. This is particularly applicable to an evacuation procedure. Proulx and Sime [4] demonstrated how crowds responded to five separate evacuation exercises from an underground station. In each case the level of communication was altered, which affected the evacuation time. These ranged from a ringing bell to use of station staff in conjunction with directive public announcements from a control centre. Clarity is essential. Evacuation times stated in design standards do not generally include a start up time. Immediate movement is assumed. Sime [5] noted that the time to escape should include an additional factor, the "time to start to move". This factor may be split into two sub-factors; the warning time (for example the time from the outbreak of fire to members of the crowd knowing there is a problem) and the start up time (which ends when movement starts). At the Beverly Hills Supper Club, Kentucky, U.S.A. [6], there was a 20 minute delay between the outbreak of a small fire and certain patrons becoming aware of the danger: 165 people died. In addition, an apparent reluctance to move was reported in a fire at Woolworths, Manchester [7]: 11 deaths.

3.4 Operational Implications

A crowd management plan should be a flexible tool, which can be modified, expanded or contracted to fit the requirements of each particular event. There will probably be more than one basic plan for multi-purpose venues . There are a number of factors influencing the management plan for a particular event or activity, which can be placed into four broad categories: the event, the crowd, the location and the time. Berlonghi [8] has produced a paper which comprehensively covers planning for the spectator crowd.

4. CONCLUSION

Crowds should be managed, using a systems approach, wherever possible. The basic principles of crowd management are to provide an effective service and provide patrons with a pleasurable experience. Control should only be used as a last resort. Crowd control measures are occasionally implemented too soon, which can cause an adverse reaction. Whenever there is a necessity to use crowd control measures, these should form part of the predetermined management plan. In unforeseen circumstances, judgement must be based upon experience and an understanding of crowd behaviour.

Most crowd incidents can be prevented by clearly defined management strategies. Triggering rapid group movement and the occurrence of critical crowd densities should be avoided. Operations managers should have an understanding of previous crowd portents and disasters to appreciate how such occurrences can be avoided in the future. Crowd management procedures should be open to review at regular intervals. This review should be based upon experience.

Frequently, the weak link in a crowd management strategy is that of communication. Decisions can only be made on accumulated knowledge, real, perceived, true or false. This applies to both the crowd and those managing them. An increase in the use of smoke alarms, visual displays and public address systems could mean that, whilst providing the crowd with information enabling them to react rationally, warning times are reduced. In turn, this would reduce the need to implement crowd control procedures in certain instances.

Effective training of staff is a vital aspect of crowd management. Their skill will be relied upon to implement a management plan successfully. Each member of staff must have a clear understanding of their responsibilities and how they should react to certain sets of circumstances. It is staff members who come into contact with the patrons. The way in which they act can influence the crowd behaviour. Dissemination of knowledge and experience internally and externally between staff and managers is essential.

REFERENCES

1. FRUIN J.J., The Causes and Prevention of Crowd Disasters. Engineering for Crowd Safety, edited by R.A.Smith and J.F.Dickie, Elsevier Science Publishers. Amsterdam, The Netherlands. 1993.

2. WANLESS, G.K., Crowd Safety. M.Sc Thesis. Manchester University, Manchester. 1992.

3. THE TIMES. 1883. 1st June, p5.

4. PROULX G. & SIME J.D., To Prevent "Panic" in an Underground Emergency : Why Not Tell The Truth? Fire Safety Science : Third International Symposium, edited by G. Cox and B.Langford. Elsevier Applied Science. Amsterdam, The Netherlands. 1991.

5. SIME J.D., Crowd Psychology and Engineering : Designing for People or Ballbearings? Engineering for Crowd Safety, edited by R.A.Smith and J.F.Dickie, Elsevier Science Publishers. Amsterdam, The Netherlands. 1993.

6. SIME J.D., Crowd Safety Management and Communications in Disasters. Management of Safety, Health and Environment, Postgraduate Course. Module 2: Evaluation and Control, edited by L.H.J.Goossens. Manual 2, Chapter 9. Top Tech Studies / Delft University of Technology. 1992.

7. SIME J.D., Human Behaviour in Fires Summary Report. Report No.44. Fire Brigades Advisory Council. Joint Committee on Fire Research. Home Office, London. 1992.

8. BERLONGHI A.E., Understanding and Planning for Different Spectator Crowds. Engineering for Crowd Safety, edited by R.A.Smith and J.F.Dickie, Elsevier Science Publishers. Amsterdam, The Netherlands. 1993.

Engineering for Crowd Safety

Projet en vue de la sécurité des foules

Projektieren für die Sicherheit von Menschenmassen

Michael DICKSON
Structural Engineer
Buro Happold
Bath, UK

Michael Dickson, born in 1944, was educated at the Cambridge Univ. , UK where he gained a degree in Mechanical Sciences and Cornell Univ., USA where he took a Masters Degree in Structural Engineering and Town Planning.

SUMMARY

This paper describes a method of appraisal by spectator capacities within a framework understood by management and determined by the characteristics and conditions of the ground and the skills of the management. Passive and active elements of crowd management within the overall procedure of appraisal are given, and engineering values for crowd loadings and barrier design are discussed in relation to acceptable stand capacities.

RÉSUMÉ

La communication présente une méthode d'évaluation de la masse de spectateurs dans un lieu public, en fonction des caractéristiques de l'installation et des possibilités de gestion du mouvement de la foule. Les éléments actifs et passifs de cette gestion revêtent une importance réelle dans cette évaluation. Les données techniques des charges dues aux déplacements et le dimensionnement des barrières et palissades sont à confronter à la capacité admissible des tribunes.

ZUSAMMENFASSUNG

Der Beitrag beschreibt eine Methode gedacht für das Management zur Beurteilung des Zuschauerfassungsvermögens abhängig vom Zustand der Anlage und der Managementfähigkeiten. Bei der Beurteilung spielen aktive und passive Elemente des Zuschauermanagements eine Rolle. Die Ingenieurdaten für die Belastung durch Menschenmassen und die Bemessung von Abschrankungen werden in Beziehung zu zulässigen Tribünenkapazitäten gesetzt.

INTRODUCTION

Over the last century the United Kingdom has built up a widely ranging stock of sports grounds, leisure and sporting facilities. In the case of football stadia, facilities were added in a piecemeal way as the fortunes of clubs prospered but often without proper thought for future planning and maintenance, so essential to public safety (Ref 1).

Attendances peaked in the 1960s and, except in individual key fixtures, are now considerably less - perhaps only 17 million as against 40 million per season. This decline in attendances has led to further pressure on the ability of grounds to fund new better facilities - ones more orientated to the modern community - or to adequately maintain or manage these facilities.

The direct result has been instances in which some facilities have failed in an engineering sense to provide for the necessary public safety with the results that accidents - often during key fixtures - have occurred. Ibrox, Birmingham, Bradford etc - are cases in point. Despite wide reporting of these instances, to the contrary, in statistical terms football spectating still remains statistically safe (between 1945-84 English League attendances of 1,100,000,000 with less than 50 fatalities which is a comparative death risk per hour/10^8 of about .001 - or 1/100 of that of death risk from fire while still at home watching the match on television.

A few years back Britain had three separate major problems at football grounds in a very short period: a bad incident at Birmingham, a wall collapse when conflict in the crowd between British supporters and others led to a crowd surge at Hysel Stadium, and a bad fire in a stand at Bradford. All led to loss of life and a government inquiry was set up. After its report the Institution of Structural Engineers, using past research, started to produce a new code of practice for appraising such grounds but before it was published there was another disaster at the Sheffield Wednesday ground which led to another government inquiry. The code subsequently produced contains the experience of these incidents. This paper is about this work. A conference was held subsequent to it and the author recommends interested people to read both documents. (Ref 2 and Ref 3).

Basic Requirements for Stadia

It is perhaps remarkable that arenas such as the Coliseum in Rome of elliptical form surrounded by tiered seating and with provision for sun shading vela are so similar to modern stadia even though at 1:19 the tiers are rather steeper than would be allowed today. It has even been calculated that the 50,000 capacity of the Coliseum could be exited at today's rates through the 80 exits in 8 minutes - similar to today's standards where stands are of mainly incombustible construction.

Much has been written on the necessary standards for sports stadium for various uses (Ref 7). Suffice to say that the plan forms ideal for good viewing football need to keep the spectator within 90m from the centre spot or 150m from the furthest corner. If space is limited, stands on the west side should be preferred, so more can view the game with the sun behind them.

Clearly, in order to fit more people into the ground, added tiers are the best solution. Straight tiers of increasing slope are cheaper but require more land. Layered tiers are more expensive but have the advantage of bringing the viewers closer to the game which, for smaller objects such as hockey, tennis, etc may be critical.

This leads to a series of physical solutions to problems relating to the free flow of people entering and leaving, the dangers of crowd pressure and, certainly for older stadia, the risks of fire and smoke. Add to this crowd behaviour and the breadth of the problem starts to be understood:

The Problem:

It is obvious that the lack of uniformity of stadia - and of people - is such that one has to see appraisal as a systems problem:

Sports grounds are aggregations of enclosures for large number of people to arrive, be comfortable and safe in and to easily depart from under a wide range of operating conditions

It is essential to understand location (and image) within the city infrastructure needs to be clearly understood, so that controlled entry (and exit) and suitable provision for access, parking, signage and provision for emergency services can be made.
Overall layout and its individual elements and sub-enclosures have to be clearly defined by drawings. So that enclosures, crowd flow networks and spectator reservoirs can be identified and then corroborated by inspection.
The structural configuration and condition understood.
Fire safety and other emergency potentials.
The way management plans its activities, organises the ground, the stewards and supporting equipment.

The Process of Appraisal:

There are four principle aspects:

Assessment of acceptable capacities both of individual enclosures and for entry/exit and evacuation to prevent crowd densities ever exceeding safe upper limits.
Appraisal of the condition and compliance of all structural elements so that adequate factors of safety against collapse remain at the accepted upper limits of crowd density.
Examination for fire (or other emergency) safety.
Survey of the constructional condition of all elements to eliminate sub-standard fabric, tripping, hazards, hazards of combustion etc.

Appraisal needs to be comprehensive if it is to be reliable. It is the application of logic and method to the scale of the problem at hand under the judgement of a competent person which is the creative part of the process. [Fig 1]. Appraisal has to be tailored to match the size and type of ground under consideration and the type of match or venue. A large ground or an especially high profile event clearly needs more refined appraisal than does a small low capacity event.
When high or unusual attendances are expected, appraisal may need to be refined in order to justify these high occupation levels. Such circumstances may require the upgrading of both

'passive' fabric elements of the ground and 'active' stewarding and crowd management provision and further evaluation of various emergency "What if?" scenarios. Potential disruptive behaviour by the crowd, outbreak of fire or other reasonable credible emergency scenarios are likely to form part of this further stage of assessment. This should include further probing of the preparedness of crowd management functions.

1. **Appointment of a Qualified Person** - Responsible for the terms and conditions of the safety certificate.
2. **Terms of Reference for Appraisal** - Sufficiently wide to ensure that the ground and its individual parts fits together as a safe system under all likely 'what if' situations.
3. **Information Gathering** - Collection of formal drawn information representative of the operation of the arena and condition of the ground and its elements.
4. **Inspection** - Inspection by a competent person of all entrance areas, stairways, ramps, viewing areas etc. for any hazards, checking geometrical compliance, identifying principal enclosures, inspecting all barriers and handrails for spacing and layout. Identify potential fire hazards.
5. **Initial Assessment** - The safe maximum capacities of each viewing enclosure will need to be checked in view of actual condition and configuration.
6. **Testing of Barriers** - and record results. Modify acceptable capacities if necessary.
7. **Inspection During Use** - To witness the interaction of 'passive' and 'active' functions of crowd control, and the quality and organisation of the stewarding, fire detection and fire fighting power.
8. **Report**

Figure . The procedure of appraisal

Once complete, the results of the appraisal needs formalising with at least the following documents :-
City plans, showing location of facility within infrastructure.
Plan and section for individual stands and their capacities together with flow networks and relevant reservoir capacities and net densities. Together with seating arrangement and standing arrangements.
Staircase arrangements for location of barriers, split-up areas.
Entry, exit, turnstiles showing location of barriers, split-up areas.
Résumé of main stand capacities by individual enclosure their turnstile and exit capacities.
Stewarding plan.
Fire Plan.

Copy of attendance and incident log for all previous venues and fixtures.

Assessing the Maximum Acceptable Capacity for a stadium is not an exact science and much further research is required.

Patterns of crowd flow, densities and capacity are only available for empirical observation (Ref 4, 5 & 6) and so a robust judgement should be applied.

Safe capacity of single enclosure

Capacity in an all seated enclosure is those seats within 14 seats of a gangway and where no seat is more than 30 metres from the nearest exit to a place of safety following the direction of the seats and gangway. Configurations of header barriers at exit staircase will need to be such that the total exit width from a particular enclosure is sufficient to allow evacuation within the Available Safe Evacuation Time (ASET).
Clearly for disabled people there are problems encountered with step seating, where evacuation has to take place without causing disruption to the majority exiting. Planned escape routes for the disabled will need to be complemented by a well rehearsed management procedure for such an emergency if overall Acceptable Capacities are not to be affected.

Normal bodied crowds are comprised of people of many shapes and sizes whose average body size can be based on a body ellipse occupying about $0.135m^2$ ($1.5ft^2$) (74 persons per $10m^2$). Occupation of sub-way cars and similar close packed circumstances results in a 450mm x 600mm body ellipse with an equivalent area $0.21m^2$ ($2.3ft^2$). This in reality is a density of 47 persons per $10m^2$ and equates to the higher but tolerable levels for queuing densities. Capacity of any standing area can then be assessed by the following :-

$$C = \frac{47}{30} \times A_e \times C_f$$

A_e = the net area (m^2) for spectators less gangways, areas for which barrier allocation is substandard and from which the event cannot clearly be seen.

C_f is a number from 1-3 reflecting the general condition of surface and repair of the enclosure.

In reality within any individual enclosures densities up to 54 person $10m^2$ and slightly beyond are safe and would enable reasonable conditions when based on the net area of occupation. Arrangements for ticketing and control into a particular enclosure have to ensure that this calculated capacity C cannot be exceeded. Active stewarding is then necessary to ensure that even densities of occupation are achieved.

Capacity of Enclosures for Safe Evacuation

Notional evacuation, times should not exceed 7 minutes since the expectation is that crowds can become restive if longer departure times are experienced. [Ref. 6]. However the capacity of most enclosures or grounds will be determined by the concept of the Available Safe Evacuation Time in a fire or other emergency situation. (ASET) The duration to be allowed for emergency evacuation depends on the range and configuration of safety criteria of which perhaps access to a place of safety is the most significant. The ISE report goes some way to organising these criteria to enable rational choice of appropriate time. Depending on the fire safety of the particular stand periods of between 2.5 and 4 minutes would seem appropriate for stands of category 1 construction (which are stands of potentially more combustible materials where it is possible to justify that lateral spread of fire will not inhibit escape or fire fighting operations). For category 2 stands which are of essentially compartmented incombustible construction and where all means of escape are adequate in respect of potential smoke logging, times of between 4 minutes up to a possible maximum if 8 minutes are acceptable. Safe escape times for either category can only be increased beyond the minimum by the incorporation into the Operating Manual of additional safety measures.

In determining capacities by this concept the other variable results from the human component as defined by maximum flow rates that are appropriate for safe (or comfortable) evacuation. Design for the passage widths for crowd evacuation through portals, along passageways, up and down ramps and stairs needs to be based on a choice of acceptable flow figures. Choice of clean forms without hazard or discontinuity and the selection of proper splitter and header barriers should affect the chosen design flow figures. Much further research of these values either by observation, and/or by development of suitable physical, analog or numerical flow models of crowd flows is urgently required.

For appraisal 'The Guide to Safety at Sports Grounds allows the figure of 40 persons per unit width along stairways (whether up or down) and 60 persons per unit width along passageway and through portals. A unit width is defined as a complete unit of 550mm assumed to be free from obstructions and hazards liable to cause tripping, etc.

Evacuation Rates	Portals/Passageways	Persons/unit width/min.	Stairs Down/Up	Persons/ unit width/ min.	Notes
Green Guide		60		40	
From Journal flow F Sports Stadia Design Terminals	26 p/ft/mm 21-26 p/ft/mm	47 37-47	21/19 p/ft/min 15/12 p/ft/min	39/35 27/22	Down/up stairs
Department of Transport TD 2/78	20p/ft/min	37	14p/ft/min	26	
SICON Observation Gateway Observation Passageway	35p/ft/min Peak 24p/ft/min Average 24p/ft/min Maximum 20p/ft/min Average		25p/ft/min ·20p/ft/min		Averaged are 7 minutes
Turnstiles peak from H.S. E. Study for Hillsborough	Peak Average	1000p/hour 680/hour			From Hillsborough report
Green Guide *		660/hour			Actual figures must be proven, if less then use in calculation.

Figure . Pedestrian flow rates

The suggested flow rates when multiplied by reasonably assessed ASET times give performance requirements in relation to exit widths, stair widths etc. which have generally to date give safe results. Nevertheless it can be seen from Figure that the actual flow rates suggested are in fact higher than those recommended by the Department of Transportation for use in pedestrian subways and higher than those recommended for unit width of sports stadium design and passenger terminal usage within the USA. For category 2 stands, American usage, tolerates longer ASET times combined with smaller flow rates/unit width resulting in roughly similar Acceptable Capacity but in supposedly more comfortable conditions for the spectator. [Ref. 7].

Conclusion

Design of safe and comfortable venues for spectators or its appraisal is a difficult task and requires many judgements to be made during the process if it is to gain a reasonable degree of safety for spectators under all operating conditions. Wide ranging engineering knowledge is required to be used with a reflective spirit. Above all the process has to interact with the practicalities of managing, operating and controlling real crowds. The essential linking commodity is a reliable address system coupled to clear and unambivalent signage. The subject requires considerable further research.

References

Ref 1. The Football Grounds of England and Wales. Simon Inglis. Willow Book. 1983.

Ref 2. Appraisal of Sports Grounds, May 1991, Institution of Structural Engineers.

Ref 3. Engineering for Crowd Safety. Edit. R A Smith and J F Dickie. Elsevier. 1993

Ref 4. Fruin J. J. Pedestrian Planning and Design, Metropolitan Association of Urban Designers and Environmental Panelists, 1971.

Ref 5. Pedestrian Subways Layout and Dimensions, Department Standard TD2 78, Department of Transport, 1978.

Ref 6. Safety in Football Stadia a Method of Assessment, SICON Report 1972.

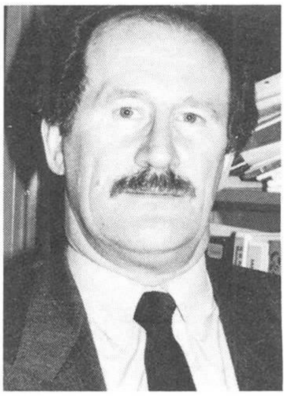
Ref 7. Standard for Assembly Seating Tents and Membrane Structures, NFPA 102, National Fire Protection Association, Quincy, Massachusetts, 1986.

Effect of Design on Crowd Safety and Calculation of Safe Capacity

Influence du projet sur la sécurité du public et capacité d'un stade

Entwurfseinflüsse auf die Zuschauersicherheit und Stadiumskapazität

Brian A. STICKLEY
Civil Engineer
Directorate of Works
Lodon, UK



Brian Stickley, born 1943, member of I. Struct. E. 1968. Technical adviser on "Safety at Sports-grounds Act", drafted the accompanying "Guide". Member of technical working parties on Popplewell and Taylor Inquiries. Member of working parties drafting all editions of the "Green Guide". Advises and lectures on the application of the Guide.

SUMMARY

Design, redevelopment and assessment of stadia must consider crowd movement, control and safety. In addition to location, type of accommodation, nature of the events and capacity, other areas must be addressed. Operation of the stadia has to include ingress, viewing and movement during the event, egress and emergency evacuation. Safe capacities must be calculated, taking into account existing conditions, the nature of the event and the effect on spectators, particularly their need for movement.

RÉSUMÉ

Le projet, la réhabilitation et l'évaluation des stades doivent tenir compte du mouvement, du contrôle et de la sécurité des masses humaines. Outre la situation, la nature et la mise en place de la manifestation et la capacité du stade, il faut aussi considérer le contrôle des spectateurs pendant leur entrée dans le stade, leur sortie normale ou leur évacuation d'urgence, tout comme pendant la durée de l'évènement. L'auteur expose les moyens de déterminer avec sécurité la capacité du stade, en fonction des conditions locales, de la nature de la manifestation et du besoin de mouvement des spectateurs.

ZUSAMMENFASSUNG

Der Entwurf, die Erneuerung und Beurteilung von Stadien muss die Bewegung von Menschenmassen, ihre Lenkung und Sicherheit einbeziehen. Neben der Lage, Unterbringungsweise und Art der Veranstaltung sowie des Fassungsvermögens ist die Kontrolle der Zuschauer beim Betreten, Verfolgen der Veranstaltung, Verlassen der Anlage und bei Notevakuierung zu beachten. Der Beitrag behandelt die Ermittlung der sicheren Personenkapazität auf der Basis vorhandener baulicher Randbedingungen, der Art der Veranstaltung und ihrer Wirkung auf die Zuschauer.

1. DESIGN OF SPORTS STADIA

From an engineering aspect, in the designing of any building or structure, the first steps are to establish a brief and ascertain the likely loading conditions. The same principles apply in the designing of a sports stadia ie. by establishing the operation of the stadia the loading conditions and design criteria are established.

Although sports stadia are designed in theory for the holding of sporting events, in many ways their main function is the accommodating of spectators, frequently in very large numbers. Whether the stadia is an existing one, an existing stadia subject to major redevelopment, or a newly designed stadia, with regard to spectators they must allow for:- ingress, viewing and movement during the event, and exiting (both normal and emergency).

Although these criteria appear self apparent, the legislation and Guides which control stadia design and assessment were only introduced and developed as a direct result of disasters. In the main three:- Ibrox - 1971 [1], Bradford - 1985 [2] and Hillsborough - 1989 [3].

The initial legislation itself [4] followed the Ibrox disaster as did the original Guide to Safety at Sportsgrounds (The Green Guide) [5]. Of the subsequent editions of the Green Guide the major revisions followed the incidents at Bradford and Hillsborough.

One of the main problems that has occurred over the years in developing the editions of the Guide as a basis for assessing safe capacities of sports stadia, are the continued statements that "we have never had an incident".

The tendency is always to concentrate on past incidents rather than looking for the potential for hazardous situations which may cause further incidents, which must be the way forward. That is not to say that we are advocating absolute safety or that stadia are dangerous. Where crowds of spectators, in the order of say 30,000 are gathered, it is unrealistic to look for absolute safety but it must be recognised that there are potential dangers. What can be established are conditions which allow spectators to enter, view and move during the event, and exit in reasonable safety.

1.1. Ingress

The initial element of ingress is the means of gaining admission and the flow into the ground will be controlled by the nature and design of the turnstiles, the method of payment ie. all tickets, cash payment etc and the skill of the operator. Such arrangements will dictate the likelihood or otherwise of queues of spectators building up. Although this is not necessarily within the precincts of the ground, consideration must be given to the safety of spectators forming such queues.

The flow rate through the turnstiles should be commensurate with the flow rate that is possible via the ingress routes to the desired viewing positions. Care should be taken that on these routes franchise outlets, toilets etc do not in anyway obstruct the route or generate queues which could obstruct the routes. Wherever possible such facilities should be barriered off in an area to one side of the route, such barriers should be designed and arranged to prevent excessive pressures building up in the queues or in spectators flowing past.

Wherever possible the turnstiles should have a direct link to the viewing area without crossing over other movement routes and should be clearly signposted to the viewing positions, facilities, franchise outlets, toilets etc.

Clearly the point of access to the precincts of the stadium should be as close as possible to the appropriate viewing area and in the design or alteration of new stadia this is an essential element to be taken into account in the initial stages of design.

1.2. Viewing and movement during an event

Unobstructed viewing for all spectators, whatever their physical build, is essential if pressures and turbulence are not to be created by spectators straining to see the event. Where a viewing area does not provide a full view of the event it should be discounted from the calculations in assessing capacity, and be kept out of use during the course of the event. Spectators should also be able to leave and regain their viewing position during the course of the event.

Considerable debate has taken place over the years with regard to crush barriers on standing terraces, in particular with regard to their strength and spacing. With regard to their strength, they are to be designed or tested to ensure they are fit for purpose. That is to say they will not fail under the forces to which they may be subjected during the course or at the end of an event. The figures quoted within the Guide to Safety at Sportsgrounds are based on an assessment of what surging pressures a body can be subjected to without sustaining injury (documentation on these tests is available). With regard to spacing, the distances stated in the Guide are those over which such forces can be generated.

1.3. Egress

Whatever the theory with regard to egress, experience has shown that at the end of an event, particularly a football match held at a major ground within a town centre, virtually all of the crowd endeavour to leave immediately on the final whistle. Therefore the exit route must be designed to cater for such a situation. Similarly the egress route should be capable of dealing with emergency evacuations, either by the normal egress routes alone or by those routes in conjunction with extra emergency arrangements.

The calculations for exiting are based on the speed of movement of the crowd (flow rate), the limiting width of the exit route and the acceptable evacuation time.

The evacuation time is the time taken for all spectators to leave the viewing area and pass through any element of the exit route. The maximum time is 8 minutes but this may be reduced based on prevailing conditions ie. to a minimum of 2½ minutes from a timber stand. Interpretation is advocated based on an assessment of the potential hazard ie. fire etc.

It is essential that spectators only gain access to the egress route at a flow rate commensurate with that at which they can flow through the entire route to exit from the ground. Suitable barrier and restrictor arrangements should be placed at the exit from the viewing area to provide a smooth and controlled flow. It is also desirable that egress routes lead directly wherever possible to the final exit from the ground and do not cross other exit routes. As with ingress routes, where exit routes combine this should be arranged in a smooth manner and due account taken of any narrowing that may occur at such junctions when establishing the limiting width of the exit route.

2. CALCULATION OF SAFE CAPACITY

2.1. What is safe capacity?

The safe capacity of a stadia is the summation of the safe capacities of the individual viewing areas of the stadia. For each area that being the lesser of the figures calculated by assessing:- ingress, viewing and exiting, based on the prevailing conditions at the time of the assessment. It is not acceptable to take into account proposed future works, should improvements etc be undertaken following the assessment of safe capacity, a re-assessment should then be undertaken to establish whether such works have provided conditions which will allow an increase in the capacity.

2.2. Factors to be taken into account when calculating safe capacity

2.2.1. **The prevailing conditions** - As stated these are the conditions that exist at the time of certification. In many respects this is the area where the application of professional judgement by those undertaking the assessment is the key factor. Ie. where underfoot conditions are such that tripping hazards are created the judgement must be made as to whether they are such that spectators should not be allowed to view from or move over such an area. If this is the case it should be fenced off and taken out of use and out of the calculations. Alternatively a reduced density may be acceptable to enable the area to remain in restricted use and a commensurate limitation placed in the calculations. Similarly where elements of the ground, such as walls, offer a potential hazard, particularly if subjected to pressures from the crowd, a decision must be made as to whether the area can be used at all or could be occupied or used on a limited density basis.

2.2.2. **Constraints dictated by the construction and location of the ground** - This takes into account the actual location of the ground, for instance its connection to the public highway ie. spectator access points. If it is only possible to gain access to the stadia from one side there will be a need to provide routes for access and egress to traverse the stadia to the various viewing areas without creating crowd disruption and confusion. The formation of such routes may well limit the capacity of the ground unless considerable work is undertaken.Similarly if direct access is not possible to individual viewing areas then controlled sub-divisions may be required at various locations on the route.

2.2.3. **Testing** - To some extent testing of barriers has been dealt with earlier, although testing is not simply limited to barriers it is required for any element of the ground which may be subjected to pressures from the crowd, the strength of which cannot be readily determined. This would include handrails, walls and the like particularly on the exit routes. The undertaking of such testing is essential to enable a proper assessment as to whether that element is fit for purpose, or as to whether any restrictive factors should be taken into account in the calculation of the acceptable capacity. This is more readily apparent for crush barriers on terraces but where it occurs within the entry or exit routes there may well be a need for the exercising of professional judgement as to what the appropriate limitations should be.

2.2.4. **Crush barrier spacing** - The recommendations contained within the Guide to Safety at Sportsgrounds are based on considerable studies and research and although a degree of flexibility is acceptable the principles must be adhered to if a safe condition is to be achieved. Non compliance will result in a reduction in available viewing area and therefore a reduced capacity.

2.2.5. **Maintenance** - Once the assessment and the safe capacity of a ground has been established it is clearly necessary to maintain the ground to at least the standard at the time of certification. Should the ground be allowed to deteriorate this would in effect be a breach of the conditions of the certificate and, particularly if an incident occurred, the club could find itself in a very serious situation. Should the local authority become aware of such a deterioration, a reassessment of the ground should be undertaken and a commensurate reduction in the acceptable capacity established. The certificate should then be amended accordingly.

Over the years inspections of grounds have shown that many problems do arise due to a simple lack of day to day maintenance. The Guide does recommend local inspection of the ground after an event, this is to establish whether any damage or defects have developed which should be rectified prior to the next event.

2.2.6. **Future improvement/upgrading** - The benefits of establishing a longer term strategic development plan for a stadia are self evident. The club can invest in its ground commensurate with its needs available finance or wishes to increase the safe capacity. Clearly a club in a lower division may well be content with a restricted capacity but on promotion would quite probably wish to increase that capacity and must therefore have plans for development in place to achieve this. A long term strategic plan would also mean that any investment was made in the most beneficial manner and with a clearly established long term objective.

2.2.7. **Controlling and monitoring capacity** - It is also essential that the actual capacity of the ground, and the distribution of the spectators, on an event day does not exceed the capacities stated within the certificate. Therefore suitable monitoring/counting systems together with a spectator distribution system which controls movements to the appropriate viewing areas, are essential. Without these the whole principle of certification fails to be effective. Where such monitoring and control distribution systems do not exist, or are not considered adequate, there may well be a need for a further reduction in the stated capacity so that any broadbrush assessment or minimal controls would still ensure a reasonable and acceptable standard of safety.

2.2.8. **Stewarding and CCTV** - However well designed the stadia, during the event itself there is no substitute for a properly set up management team. Properly trained stewards are essential and when coupled with a strategically distributed CCTV system should enable effective crowd management.

3. SUMMARY

In the limited time available it is not possible to go into detail on the development of the Guide or its objectives, these principles however are set out within the body of the Guide. What has become apparent over the years with the development of this document is that all of the legislation and the various editions of the Guide are disaster led. All too soon after an incident the promised good intentions to undertake reviews and enforce changes are forgotten. It appears sometimes that the industry wishes to be legislation led and will only make the moves forward that are clearly necessary, when the requirements are imposed on them.

I have endeavoured to set out the basic parameters on which the legislation was based and the Guide developed initially and subsequently revised. The objective never has been to attempt to achieve absolute safety, clearly that could not be practical. However over the years we have become totally convinced that it is possible to make a calculated assessment of a ground and establish capacities which can be accommodated with reasonable safety in designated areas. It is not the Guide or the Legislation which create safety, it is the correct application/interpretation etc of the information available coupled with the application of professional judgement by those designing, managing and certifying the grounds. Followed by adherrance to the conditions/restrictions of the certificate when the ground is in operation.

In the past, when an incident has occurred, the main objective seems to be to allocate blame rather than identify the actual cause. At Bradford and Hillsborough sufficient information was contained within the Guides in use at the time to have at least identified the potential for the incidents. Appropriate action to deal with such matters when identified would go a long way to either avoiding them or at least greatly reducing their catastrophic effects. Until full and realistic appraisals are made of grounds in line with the parameters laid down in the Guide, and other guidance which is available, are applied objectively together with a full professional input, there will always be a potential for such incidents.

What is proposed is an objective engineering based approach using professional judgement and flexibility to produce an acceptable standard of safety.

REFERENCES

1. IBROX - Report of the Inquiry into Crowd Safety at Sports Grounds - by The Rt Hon Lord Wheatley May 1977.

2. BRADFORD - Committee of Inquiry into Crowd Safety and Control at Sports Grounds - Final Report January 1986.

3. HILLSBOROUGH - The Hillsborough Stadium Disaster 15th April 1989 - Inquiry by The Rt Hon Lord Justice Taylor - Final Report January 1990.

4. Safety of Sports Grounds Act 1975.

5. Guide to Safety at Sports Grounds - 1973/1976/1986/1990.

Key Crowd Safety Issues in the Design of Public Venues

Conception des lieux de réunion et critères de sécurité

Konzeption von Versammlungsstätten Sicherheitskriterien

S.Y. Zachary AU
Consultant
R.M. Consultants Ltd
Warrington, UK

Zachary Au specialises in crowd safety and ergonomics. He is one of the key authors of the UK Health and Safety Executive (HSE) research report on crowd safety. He has also carried out crowd safety assessments for a number of clients.

Michael S. CAREY
Consultant
R.M. Consultants Ltd
Warrington, UK

Michael Carey was the project manager and is a co-author of the HSE report. He has also been involved in a variety of crowd safety projects. His specialist interest is evacuation from offshore installations.

SUMMARY

This paper concentrates on the hazards that can arise from crowd behaviour and their implications on venue design requirements. It also argues that there are benefits in adopting a systematic approach to the assessments of risks during the design stage of a development project. A proposed approach to crowd safety risk assessment is briefly described. This paper is based on a major research project on crowd safety completed by the authors for the UK Health and Safety Executive. The results of the research form the basis for guidance on crowd safety planning in the UK.

RÉSUMÉ

L'article expose la valeur d'une méthode systématique d'évaluation des risques dans une phase d'étude initiale, relative aux dangers résultant du comportement des foules et qu'il faut prendre en compte lors du projet de lieux de rassemblement. La réflexion méthodique ainsi présentée se base sur un projet de recherche de grande envergure entrepris par les autorités britanniques de la santé et de la sécurité et dont les résultats ont d'ailleurs été utilisés pour établir des recommandations nationales en la matière.

ZUSAMMENFASSUNG

In Betrachtung der Gefahren, die aus dem Verhalten von Menschenmassen erwachsen und beim Entwurf von Versammlungsstätten zu berücksichtigen sind, wird der Wert einer systematischen Vorgehensweise bei der Risikobeurteilung in einem frühen Planungsstadium aufgezeigt. Die vorgestellte Betrachtungsweise basiert auf einem grösseren Forschungsprojekt der britischen Behörde für Gesundheit und Sicherheit, dessen Resultate in einschlägige nationale Empfehlungen Eingang fanden.

1. INTRODUCTION

Public venues refer to permanent as well as temporary places where members of the public assemble. They include transport venues, sport stadia, shopping malls, leisure complexes, concert arenas and fairgrounds. Large crowds are a normal and desirable part of the operations in many of these venues. However, the presence of large numbers of people can give rise to a variety of safety hazards. These can result from unsafe venue features, crowding problems or the existence of one or more physical threats (e.g. fire) in an emergency. Appropriate design and effective crowd management are the keys to ensuring crowd safety in public venues. The focus of this paper is on the first of these aspects. Management issues have been discussed elsewhere (References 1 & 2).

2. VENUE DESIGN REQUIREMENTS

At a general level, the most important design requirements are:

(i) To ensure that the venue provides sufficient space, access and appropriate layout to cater for the needs and activities of the crowds during normal operations and in an emergency situation.

(ii) To ensure that the structures are sufficient to accommodate the static and dynamic loadings that can occur through the above.

Adequate venue design involves more than just elimination of unsafe design features (e.g. inadequate stair design or unsafe floor surfaces), removing of obstructions, minimisation of pinch points, and creating enough space for people to stay or move around. Whilst these are important design requirements, the emphasis should be on how to cater for the <u>needs</u> and <u>activities</u> of the crowds as described in (i) above. To achieve this, the design team must carefully consider the likely crowd flows, distribution, and behaviour in their specific venue. Crowd behaviour is particularly important since it can have a substantial influence on flows and on visitor activities, which in turn determines venue design requirements. The rest of this paper discusses the implications crowd behaviour can have on crowd safety and venue design. It also outlines a systematic approach to the assessment of crowd safety risks during the design phase of a development project.

3. CROWD BEHAVIOUR

3.1 Understanding Crowd Behaviour

The ways people behave in a public venue is influenced by a large number of diverse factors. Some of them are directly related to venue design, others are either due to specific circumstances or associated with the individuals themselves. Nevertheless, most of these can have implications for venue design. Therefore, it is very important for the design team to identify such factors and understand their influences.

Figure 1 shows a model of the factors affecting people's behaviour in public venues. It was developed as a framework for describing the influences of various factors on crowd behaviour. The model is structured around a human response flow diagram which consists of four main stages that an individual may cycle through. The four stages are:

(i) To sense - the stage at which the individual obtains information from the surroundings.

(ii) To interpret - the stage at which the individual considers the meaning of the information.

(iii) To decide - the stage at which the individual decides upon the response required to the interpreted situation.

(iv) To act - the stage at which the individual physically carries out the plan/decision.

3.2 Factors Affecting Crowd Behaviour

Factors affecting behaviour are listed adjacent to the human response flow diagram. They are grouped in accordance with the ways in which they may affect behaviour. It is impossible to describe and discuss in detail the influence of each factor in this paper. Therefore, the rest of this section focuses on some of the more important factors and discusses the implications they may have on venue design.

3.2.1 Goals and Objectives

The reasons for attending a venue, any dominating desires or immediate needs that people have is often the primary factor in determining their activities, movement and distribution. For example, in a venue designed to hold events where there is a centre of attention (e.g. outdoor concerts, sports fixtures, racing), the primary goal of those attending is to gain a suitable vantage point in order to watch the attraction. The crowd density and hence the loading in these vantage points are therefore likely to be significantly higher than in other parts of the venue. Similarly, the access routes leading directly to these vantage points are likely to be in greater demand. In a pop concert, for example, people tend to gather as close to the stage as possible, whereas a position adjacent to the finishing line is a primary vantage point in a race meeting. Furthermore, there may be some incentive in climbing up venue features such as fences, towers (e.g. for lighting), walls and other similar structures to obtain a better view. These structures should, therefore, be able to withstand the extra loading imposed or suitably designed to prevent or discourage such behaviour.

Apart from the centre of attention, there are often other places in the venue which tend to 'attract' a large number of people. Such places include refreshment and toilet facilities. Access to and from these facilities are likely to be heavily used and should be designed accordingly. Consideration needs to be given to the location of such facilities in relation to accommodation/circulation areas, exit/entrance capacity and the physical design of the fixtures and structures in such areas.

Similarly, in transport venues where the main goal is to catch the train, plane, etc., the main 'attractions' tend to be the area in front of the departure board and the check-in area where static crowds mingle with dynamic crowds. An open area is therefore required to cater for such activities. Large number of pillars and columns can restrict movement and create crowding problems. The positioning of departure information has to also be considered to prevent unwanted localised crowding problems. In some other venues such as shopping malls and show/fairgrounds, the 'attractions' are spread across the venue and particular attention needs to be paid to crowd flows.

3.2.2 Mental Condition and Emotion

People's mental state such as aggressiveness, jubilation and emotional fever can significantly influence their activities in some venues and therefore have to be taken into consideration at the design stage. Aggressiveness can lead to confrontation between rival groups. Jubilation and emotional fever can easily lead to people jumping up and down, swaying and surging, and other similar activities (e.g. 'Mexican Waves'). These activities obviously put extra loading on the structure underneath and may pose a direct threat to crowd safety through crushing with appropriate seggregation or barrier design.

3.2.3 Knowledge, Experience and Expectations

It is important to bear in mind that people behave in accordance to their perceived environment which does not necessarily correspond to the real environment. People tend to interpret what they see, hear, etc. based upon the knowledge, experience and expectations they have developed from everyday life and past visits to similar venues. Incorrect perceptions of the layout of the venue and of the situation can result in tragic consequences, especially during an emergency (eg. the King's Cross fire in 1989). However, the layout of some public venues is so complex and confusing that way finding is difficult for people even during normal operation. Venue layout and the detailed venue features can also influence crowd distribution. For example, where there is more than one access route to a particular area, people who are unfamiliar with the venue tend to use the more obvious route. Those who know the venue well tend to use the most direct route. A potential consequence of such behaviour is overcrowding on one route whilst the others remain quiet. Inadequate consideration of flow patterns and user habits cannot necessarily be overcome by improved signage.

3.2.4 The Characteristics of the Venue

The layout of the venue, design of circulation routes, and the design and location of facilities can have a fundamental influence on behaviour and crowd flow. Physical features of a venue can be used to enhance or restrict certain behaviour, choice of routes or actions. Depending on the particular situation, this can have both positive and negative consequences and in many instances may have a knock-on effect in other parts of the venue. For example turnstiles could be useful in limiting and controlling the flow of people into an area but may result in dangerous crowd build-up outside. Similarly, barriers or fences may be positioned to segregate crowd flows or to prevent access to restricted areas, but if used inappropriately, could from part of a trap where the movement of the crowd is undesirably restricted or channelled. Other design features which could introduce negative effects on crowd safety include pinch points or bottle necks, funnelling effects, convergence of several routes into one area with limited space, dead ends, and popular places/facilities/attractions too close to each other or next to a busy junction/crossroads.

4. A SYSTEMATIC APPROACH TO ASSESS RISKS

4.1 The Need for a Systematic Approach

The previous section was intended to give a general impression of how various factors may influence people's behaviour and consequently venue design requirements. In practice, however, there can be a different combination of factors involved in a venue at different times and under different circumstances. The effect of each factor on behaviour can also vary, resulting in widely differing behaviour. It is impossible to produce a set of rules on behaviour and venue design which are general enough to suit all types of public venues and yet specific enough to be useful.

A better alternative is to systematically assess the safety risks associated with the design. This is to ensure that the venue does not pose any major safety hazards and that it is as safe as is reasonably practicable during both normal operation and in an emergency situation. Risk assessment at the design stage also helps to avoid costly modifications which may otherwise only be revealed after the venue is built.

4.2 An Overview of a Risk Assessment

The purposes of a risk assessment are as follows:

(i) To provide a systematic review of the safety risks within a venue.

(ii) To enable the hazards to be prioritised and subsequently to identify those aspects of the venue design that require the most needed modifications.

(iii) To focus attention on the design modifications required to minimise the risks to crowd safety.

In order to achieve the above, the risk assessment process generally consists of the following four main stages:

(i) Identification of hazards - This is to consider and identify the safety hazards that could exist due to inadequate design or lack of consideration to people's needs and activities. The aspects of the design which could contribute to the hazards are also identified at this stage.

(ii) Risk estimation - This is to estimate the risk level of each of the hazards identified. It involves determining, using expert judgement, the likelihood of each hazard to occur and the potential consequence should it occur. Rating scales such as those shown in Figures 2 and 3 can be used for this purpose. The risk level of each hazard can then be calculated by multiplying its likelihood and its consequence. It must be noted that the risk levels calculated at this stage are for ranking purposes only and should not be treated as an absolute measure of risk.

(iii) Risk Prioritisation - This is to compare the risk level of each of the hazards in order to determine their relative importance. In general, the higher the risk level, the more important the hazard is. Priority should usually be given to tackle hazards which are relatively more important.

(iv) Identification of measures to minimise risk - This is to identify the modifications required on the existing design in order to minimise risk in the venue.

More details on risk assessment and its applications to crowd safety can be found in References 1, 3 and 4. To maximise the benefits of risk assessment and to minimise the costs and effort involved in modifying the design, a brief risk assessment can be carried out at the end of the initial design stage on the general layout and on the main venue features. A more detailed assessment can be conducted at the final design stage on all aspects of the design.

5. CONCLUSIONS

A range of hazards can arise from the assembly of large crowds in public venues. Adequate venue design is vital to crowd safety. In general, venues should be designed to cater for the needs and activities of the crowds. In order to achieve this, careful consideration has to be given to crowd flows, crowd distribution and especially crowd behaviour. Crowd behaviour in public venues is influenced by a large number of diverse factors, many of which have some bearing on venue design. However, the ways these factors influence behaviour, and hence design requirements, varies across venues. There are clear benefits from carrying out a systematic review of the risks posed by a design. To do this at an early stage of a development project could minimise the costly safety modifications that may be required after the venue is built. It could also significantly reduce the costs and effort involved in crowd management when the venue is in use.

6. REFERENCES

1. Au, S.Y.Z., Ryan, M.C., Carey. M.S. and Whalley, S.P. (1993) Managing Crowd Safety in Public Venues: A Study to Generate Guidance for Venue Owners and HSE Inspectors (London: HMSO).

2. Au, S.Y.Z., Ryan, M.C. and Carey. M.S. (1993) Key Principles in Ensuring Crowd Safety in Public Venues. In: Proceedings of the International Conference on Engineering for Crowd Safety, London, UK, 17-18 March 1993 (Amsterdam: Elsevier).

3. Health and Safety Executive (1991) Successful Health and Safety Management (London: HMSO).

4. Health and Safety Commission (1992) Management of Health and Safety at Work: Approved code of practice (London: HMSO).

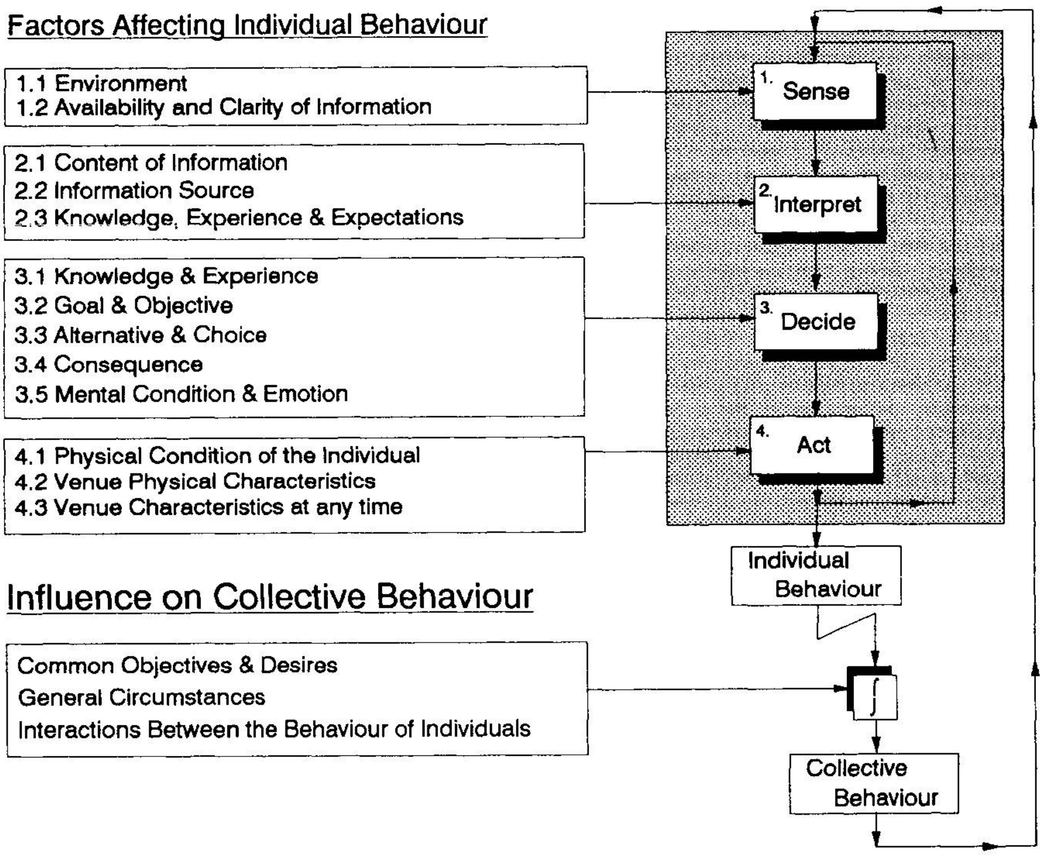


Figure 1 Factors Affecting People's Behaviour in Public Venues

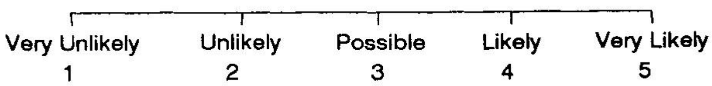


Figure 2 A 5-Point Scale for the Estimation of Likelihood

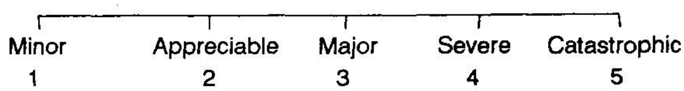


Figure 3 A 5-Point Scale for the Estimation of Severity of Consequences

Assessment of Human and Structural Safety of Sports Grounds

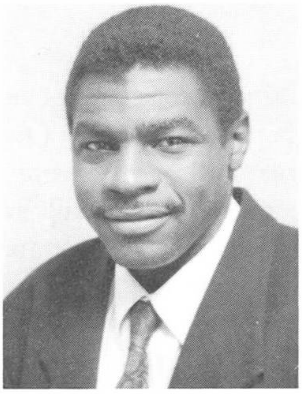
Évaluation de la sécurité personnelle et structurelle dans les centres sportifs

Bewertung menschlicher und baulicher Sicherheit auf Sportgeländen

Lindiwe RUBADIRI
Research Student
Univ. of Central Lancashire
Preston, UK

Divine NDUMU
Lecturer
Univ. of Central Lancashire
Preston, UK

John ROBERTS
Prof.
Univ. of Central Lancashire
Preston, UK



SUMMARY
This paper describes a flexible automated decision-support system for assessing the safety of sports grounds. The system focuses primarily on three factors: the occupancy, management and structural aspects. It considers overall interdependencies between these factors, and makes managerial and design recommendations for improving the safety of a venue.

RÉSUMÉ
La communication présente un système expert flexible et automatique, en vue de contrôler la sécurité des installations sportives, et qui s'appuie sur trois facteurs principaux: spectateurs, exploitation et aspects constructifs. Ce système tient ainsi compte de la dépendance réciproque de ces facteurs, ce qui conduit à des propositions d'amélioration de la gestion, mais également à des recommandations pour le projet.

ZUSAMMENFASSUNG
Es wird ein flexibles, automatisiertes Expertensystem für die Sicherheitsuntersuchung von Sportanlagen beschrieben, das sich auf drei Hauptfaktoren stützt: Belegung, Management und bauliche Aspekte. Dabei wird die gegenseitige Abhängigkeit dieser Faktoren berücksichtigt, die zu Verbesserungsvorschlägen bezüglich Management, aber auch zu Entwurfsempfehlungen führt.

1 INTRODUCTION

There has been a continual attempt to raise safety standards of places of close assembly, for example, sports grounds. Major disasters including the incidents at Ibrox stadium (1971), Bradford (1985) and Hillsborough (1989) in which many people died and extensive damage was experienced, have led to more stringent scrutiny of safety legislation. Guidelines on measures for improving safety of spectators at sports grounds first became available when the Wheatley Inquiry was published after the Ibrox Park disaster [6]. Along with the Safety of Sports Ground Act 1975, these guidelines formulated the basis of the document commonly known as the 'Green Guide' [7]. Revision of this guide resulted from the Popplewell Inquiry [11] that followed the Bradford Football Stadium disaster. Further changes were incorporated, based on recommendations made in Lord Justice Taylor's inquiry, after the Hillsborough tragedy [14]. The Guide basically outlines measures for improving spectator safety and applies to all types of sports grounds where accommodation is provided for spectators [8]. In this paper, the authors concentrate on football stadia which have a long history of major and minor crowd disorders. In addition, football attracts a large number of spectators making their safety an item of primary concern.

The assessment of sports grounds before, during and after an event is a time-consuming and costly exercise requiring much co-ordination and planning. Because of the excessive number of factors that have to be considered in the assessment process, the assessment personnel generally suffer from a cognitive overload of information. This overload tends to result in some fairly obvious scenarios not being anticipated at all, or the implications of a change in a parameter not being completely appreciated. A significant amount of assessment is done from experience but it is rightly stated [15] that, "...those dealing with disasters and their prevention know that they have to continually re-learn old lessons stated in new ways".

In order to significantly speed up the assessment of sports ground safety, and to provide a system whereby the influence of different parameters on a safety plan can be thoroughly investigated, the authors suggest a flexible model, implemented as a knowledge-based decision-support computer program that contains relevant evacuation, crowd behaviour and structural safety knowledge.

2 BACKGROUND

Evacuation modelling has been a useful technique in simulating human behaviour and movement patterns of occupants and has been used by several researchers to investigate the effects of various parameters on evacuation time and procedure [1,5,9]. In this paper, the authors have utilised certain evacuation modelling principles in the design of a safety assessment system for sport grounds.

2.1 Basis of the assessment model

Three factors are critical in affecting safety: occupancy, management and structure of football stadia. In order to identify critical parameters that operate during emergencies, and to develop relationships between these factors, the authors adopted the molecular kinetic theory of gases as the basis of a safety assessment model. The molecular kinetic theory of gases [2] relates the temperature, pressure and volume of a gas by the equation $PV = nRT$; where P denotes pressure, V volume, T temperature, n the number of moles of the gas, and R the real gas constant.

For a constant volume, the pressure of a gas varies linearly with its absolute thermodynamic temperature. Temperature is a measure of the kinetic energy of the molecules. Raising the temperature results in an increase in the velocity of the molecules and consequently, an increase in the frequency of collisions that the molecules experience with each other and with the sides of the vessel containing them. This is manifested as a pressure increase. This basic behaviour shares certain similarities with that of a large number of occupants in confined spaces, at least in the two-dimensional sense. The kinetic theory is adopted purely to generate conceptual ideas that simulate human behaviour. Differences between the two concepts have been accounted for in the assessment model.

The analogy between molecular kinetic theory and a real-life emergency on a sports ground is evident form the following scenario: Assume gaseous molecules represent occupants while the vessel containing these molecules represents the stadium. A fire, for example, on any part of a ground would stimulate some response from occupants. After they perceive the fire as endangering their lives they would attempt to leave the ground to go to a place of safety. As a result of the fire, speed of movement of occupants as they attempt to distance themselves from the danger, would most likely increase as would the number of collisions or impacts between the occupants and between occupants and the physical structures in the stand. Thus 'temperature rise' or an emergency has an effect on occupancy, management and structural aspects. Table 1 summarises some of the analogies between molecular kinetic theory and the assessment model.

Molecular kinetic theory	Assessment model
Concentration of molecules	Density of occupants in football stand
Uniform or non-uniform mixture	The distribution of occupants in accommodation areas
Type of molecules	Type of occupants present (disabled, able-bodied, young, old, in groups, etc.)
Forces of attraction between molecules	Affiliation ties between occupants
Material of the vessel	Structure of the stand
Path of motion of molecules	Movement patterns of occupants

Table 1: Analogy between molecular kinetic theory and safety assessment model

2.2 Observations from evacuation study

The kinetic theory analogy of crowd behaviour was reinforced by observations of a football stand evacuation exercise carried out at Preston North End football ground [12]. The stand evacuated was the Fulwood End terrace which has a maximum holding capacity of 3,500 occupants. The number of spectators occupying the stand on this occasion was estimated at 1,350.

Before the match, the ingress of occupants into the stand could be likened to filling a vessel with gaseous molecules. The movement of occupants to their positions appeared to be random, but in fact, they were likely to be influenced by factors such as group relationships, familiarity with the stand layout etc. From the safety point of view, an even distribution of occupants was desirable in order to avoid surging and pressure build-up near crush barriers. This was achieved primarily by effective stewarding. In the kinetic theory analogy, stirring a gaseous mixture would eventually give a uniform mixture.

At the half-way interval of the match, a cue was given to evacuate the stand. This cue can be taken to represent a 'temperature rise' which invoked a reaction manifested as movement of the occupants into the assembly area. From kinetic theory, a localised temperature rise would result in increased energy of nearby molecules, which would cause them to move at a higher velocity and experience more frequent collisions. This effect spreads throughout the mixture until equilibrium is reached. In the football ground situation, a localised hazard would cause a reaction from occupants closest to the hazard. This reaction would spread to other occupants via a 'collision effect' at a rate proportional to the degree of danger perceived to result from the hazard. During the evacuation exercise, movement was initiated by spectators nearer the front gates. These spectators set the pace of evacuation for the crowd behind them.

The occupants left the stand passing through the gaps between the barriers, moving randomly within the available space. A significant amount of queuing was experienced as occupants moved through the exits. The choice of exit appeared to be governed by proximity to the exit. This is in agreement with the behaviour of gaseous molecules which tend to flow through an available nearby opening. If an opening is surrounded by group of molecules, the remaining ones will move along the path of least resistance to find a less-crowded alternative. In the same way, during an evacuation of occupants, if queuing occurs at an exit, an alternative nearby exit is sought. In case of equally crowded conditions, where there is queuing at all exits, occupants cannot avoid becoming part of a queue.

3 A COMPUTER SYSTEM FOR ASSESSING THE SAFETY OF SPORTS GROUNDS

The molecular kinetic theory analogy outlined above served as a vehicle for identifying and developing simple condition-action rules describing the interactions between occupant behaviour, managerial decisions and structure in sports grounds. These rules incorporate evacuation, crowd behaviour and structural safety knowledge, as well as normative knowledge from the Green Guide. The rules have been implemented in computer-usable form as the knowledge-base of an intelligent decision-support system.

The computer program comprises principally of a knowledge-based component, implemented using the CLIPS 5.1 production-rule system [4], and a custom-built hypertext system, HTEX 1.0 [10]. The two subsystems are fully compatible with one another, allowing two-way information exchange. Based on a user's input specifications, the knowledge-based component makes decisions about whether or not safety requirements are satisfied at a ground. In the latter case, it recommends corrective actions, whereas in the former, it may suggest methods to improve on the safety of the ground. The recommendations arrived at may, for justification, reference relevant sections of the Guide or the research literature, which are also represented in the system (in textual form) in the hypertext module.

Hypertext systems allow the representation of normative knowledge, such as is contained in the Guide, as a network of related but independent information units [3,13]. Two units of information are linked in the network if one is referenced in the other. The network representation allows a user to transverse the Guide as he desires, following links that he deems important. This is in contrast to a flat representation which constrains the user to follow the author's chain of reasoning.

Once within the hypertext module, the system allows the user to query the status of the Guide's clauses, that is, whether they are violated or satisfied. This is achieved through a call back to the knowledge-based component. The queried clauses do not necessarily have to be the same as those in the initial recommendation that caused the jump into the hypertext module. Fig. 1 illustrates English versions of some of the rules in the system, and Fig. 2 depicts hypertext windows invoked by querying the recommendation arrived at by Rule 1. The top window shows the information displayed when the recommendation is queried, while the bottom window shows additional information displayed when the underlined phrase Stewards in the first window is queried.

1. **If** (distribution of occupants) is (locally clustered around exits) **then**
   recommend(managerial, "stewards disperse the crowd in order to attain uniform distribution")
2. **If** (pre-event planning) **then**
   data((ground assessment), needs-to-be, (routine))
3. **If** (some occupants) have (disabilities) **then**
   recommend(managerial, "proper provision should be made to accommodate the disabled occupants")
4. **If** (surveillance/communication system) needs-to-be (checked) **then**
   recommend(managerial, "perform surveillance/communication system check")

⋮

Fig. 1: Near-English representation of some of the rules in the system

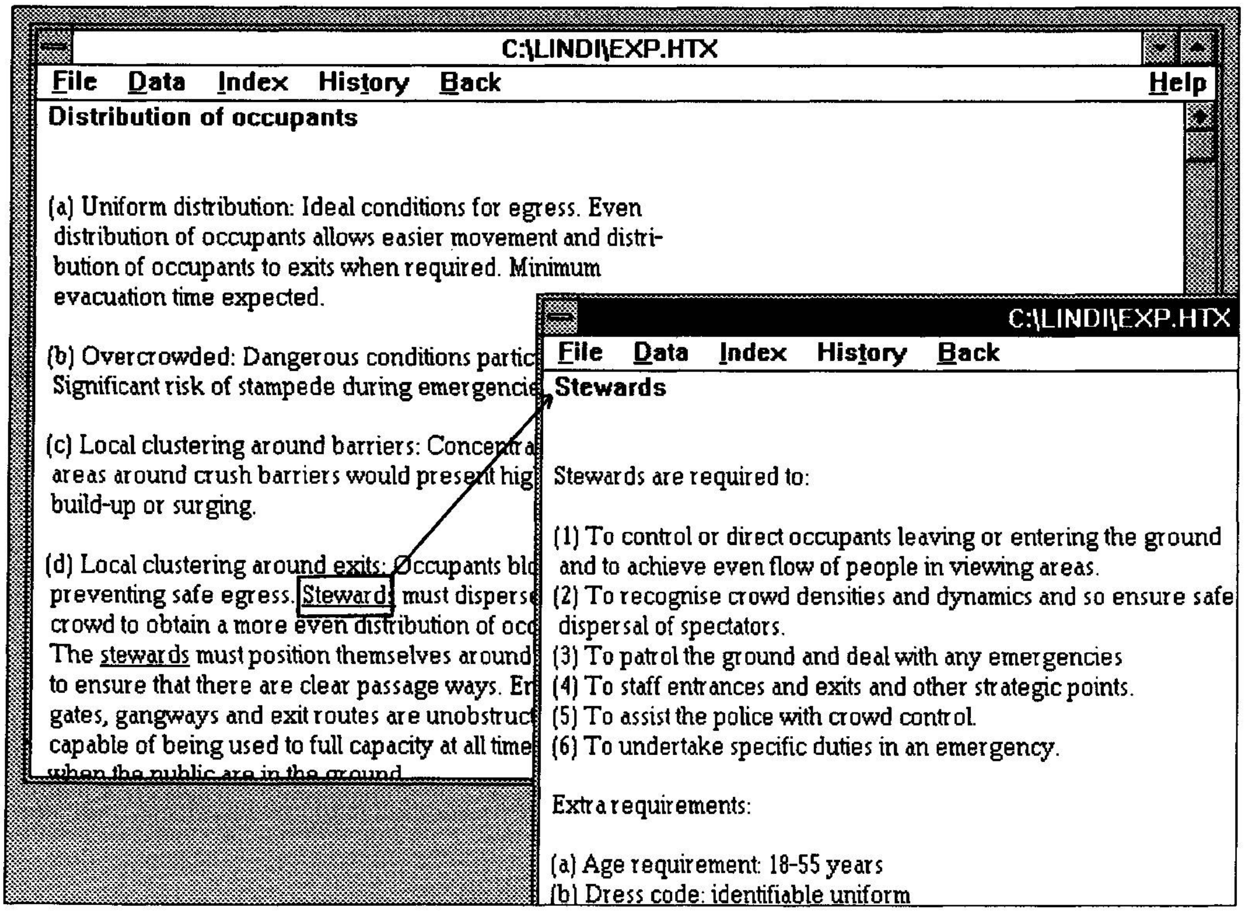


Fig. 2: HTEX windows providing further information

CONCLUSIONS

This paper has described a simple but flexible knowledge-based computer system for quickly assessing the safety of football grounds. The system considers the inter-relationships between occupancy, management and structural aspects in accommodation areas, assembly points and evacuation routes, and makes recommendations for improving the safety of a ground. This system will be particularly useful to building control and fire safety officers and management personnel. In addition, it could be used as a preliminary design assessment tool by designers of new sports grounds. The time and cost-saving benefits of the system derives primarily from automating the significant amount of paperwork involving cross-referencing of several documents inherent in conventional methods of assessment. The system attempts to unify all essential safety information, while providing a facility for incremental modification. On extension of the knowledge base, the system should be capable of being applied to a wider range of places of close assembly.

ACKNOWLEDGEMENTS

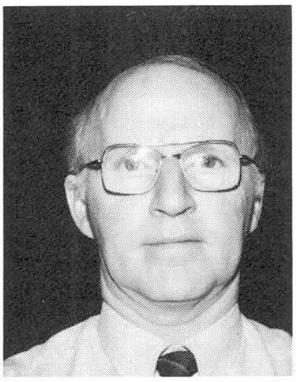
The first author would like to acknowledge the support of Mr. John Willis, Fire Safety Officer of Preston North End Football Ground. She would also like to acknowledge the assistance given by Sergeant Billsbury of Preston Police and all staff involved in organising the evacuation of Fulwood End terrace in November 1993. The support given by observers from University of Central Lancashire: Mick Ward, Pam Curwen, Gilbert Owusu, Francis Kalibala and Joseph Madida, is also greatly appreciated.

REFERENCES

[1] BEARD, A., "Towards a systemic approach to Fire Safety", *Proc. First Int. Symp. on Fire Safety Science*, (ed) GRANT, C. and PAGNI, P.J., pp 943-952, 1986.
[2] COLLIE, C.H., "Kinetic theory and entropy", Longman Group Limited, UK, 1982.
[3] FEIJO B., DOWLING P.J. and SMITH D.L. "Incorporation of steel design codes into design automation systems", *Proc. IABSE Colloq. on Expert Systems in Civil Engng.*, IABSE, v58, pp. 393-402, Bergamo Italy, 1989.
[4] GIARRATANO J. and RILEY G., "Expert systems: principles and programming", PWS-Kent Publishing Company, Boston, 1989.
[5] HINKS, J., "A Systems Evaluation of Life Safety in Fires ". PhD Thesis, University of Edinburgh, Scotland, 1988.
[6] HMSO, "Safety at Football Grounds: Wheatley Report", 1972.
[7] HMSO, "Guide to Safety at Sports Grounds", 1990.
[8] INGLIS, S. and MURRAY, C., "Terraces: Designing for Safe Standing at Football Stadia", FSADC, 1993.
[9] KENDIK, E., "Methods of design for means of egress: Towards a quantitative comparison of National Code Requirements", *Proc. First Int. Symp. on Fire Safety Science*, (ed) GRANT, C. and PAGNI, P.J., pp 497-511, 1986.
[10] NDUMU D.T., "HTEX 1.0: User manual", in press, Dept. of Built Environment, University of Central Lancashire, 1994.
[11] POPPLEWELL, "Committee of Inquiry into Crowd Safety and Control at Sports Grounds: Final Report", HMSO, 1986.
[12] RUBADIRI, L., "Fulwood End Terrace: Evacuation Exercise at Preston North End Football Ground (27th November 1994)", Research Report, 1994.
[13] SCHWABE D., FEIJO B. and KRAUSE W.G., "Intelligent Hypertext for normative knowledge in engineering", *Proc. European Conference on Hypertext*, INRIA Versailles France, 1990.
[14] TAYLOR, "Inquiry into the Hillsborough Stadium Disaster: Final Report", HMSO, London, 1990.
[15] TURNER, B.A., "Crowd Behaviour: Lessons to be learnt from Summerland". *Lessons learnt from Crowd-Related Disasters*, Easingwold Papers No. 4, Home Office Emergency Planning College. pp 55, 1992.

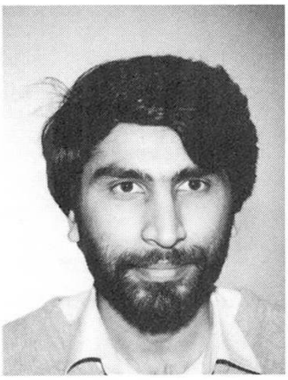
Crowd Modelling
Modélisation des masses humaines
Modellierung von Menschenmassen

J.F. DICKIE
Structural Engineer
Univ. of Manchester
Manchester, UK



Jim Dickie, BSc, PhD, (London). Principal research interest concerns the safety of the individual in public venues that attract large crowds. He has acted as a consultant in this particular area on a number of major stadia developments.

J. MEGHJI
Research Student
Univ. of Manchester
Manchester, UK



Jawad Meghji, BE, MSc. For five years he was involved in teaching and research at Quaid-i-Azam Univ., Islamabad, Pakistan. Major research interest concerns risk analyses and safety. Presently studying for a doctorate at Manchester Univ.

SUMMARY

This study develops a computational model that enables the analysis of the flow of a crowd to be examined. The placement of individuals that comprise the crowd may be random within a bounded space and the crowd density may be varied. The walking speed of the individuals is described using a Normal Distribution, the mean and standard deviation may be independently varied. The speeds of given individuals may also be specified independently of the distribution; this enables the influence of moving individuals to be examined.

RÉSUMÉ

Les auteurs ont développé un modèle assisté par ordinateur qui permet de calculer les flux de foule, compte tenu de la répartition aléatoire des individus dans un espace limité et de la variation de la densité humaine. La vitesse de déplacement est définie par une répartition normale avec variation autonome de la valeur moyenne et de l'écart type. L'attribution d'une vitesse indépendante de la variation permet d'examiner l'effet d'une masse humaine à déplacement lent et rapide.

ZUSAMMENFASSUNG

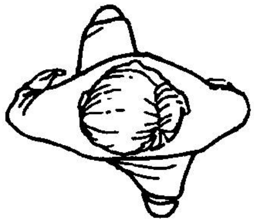
Für die Berechnung von Menschenflüssen wurde ein Computermodell aufgestellt, in dem die Personen innerhalb eines abgegrenzten Raumes zufällig verteilt sind und die Massendichte variiert werden kann. Die Gehgeschwindigkeit wird durch eine Normalverteilung mit unabhängig wählbarem Mittelwert und Standardabweichung beschrieben. Durch Vorgabe einzelner Geschwindigkeiten unabhängig von der Verteilung kann der Einfluss sich bewegender Personen untersucht werden.

1. INTRODUCTION.

The movement of pedestrians in and about crowded public areas is the concern of a number of professions. Shinjyuki station in Japan will handle 1362000 passengers daily; 70000 spectators wish to leave Wembley stadium,London, almost simultaneously; the World Trade Centre, a high rise building in New York City, has 50000 employees and an estimated 80000 daily visitors. In each of these situations the problems posed in planning for normal egress have to be integrated with emergency requirements. Central to the problem is that the physical environment of any structure or space needs to safely accommodate large flows of people. Current design procedures, embodied in codes, have evolved from empirical evidence obtained from observation. The work subsequently described presents a computer simulation that follows the progress of each individual in a uni-directional crowd moving towards a common objective. Slow moving individuals whether a large number of elderly or a single disabled individual or an individual encumbered with baggage or an individual in a hurry will all influence the flow of any body of people in which they move. The simulation allows variation of the movement characteristics of any individual or a group of individuals in a randomly spaced crowd flow. The movement characteristics of individuals within the crowd are described in a statistical manner that allows variation of mean and deviation.

2. PREVIOUS WORK.

Templer [15] describes the spatial requirements of a pedestrian and the manner in which the pedestrian systematically occupies and relinquishes space. The space required for pedestrian movement is dependent on four factors, the body ellipse, the pacing zone, the sensory zone and the buffer zone.The body ellipse represents the physical plan dimensions of the body, the pacing zone represents the space within which movement occurs. The sensory zone is the distance a person tries to maintain between the body and other parts of the environment so that there will always be enough time to perceive and evaluate and react to approaching hazards. The buffer zone is the space that people maintain between themselves and others for psychocultural reasons. In crowded spaces the sensory and buffer zones will merge and will not be present in densely crowded spaces. A conflict is any stopping or breaking of normal walking pace due to a too close confrontation with another pedestrian. A conflict does not mean actual impact; pedestrians can stop and turn with remarkable speed.



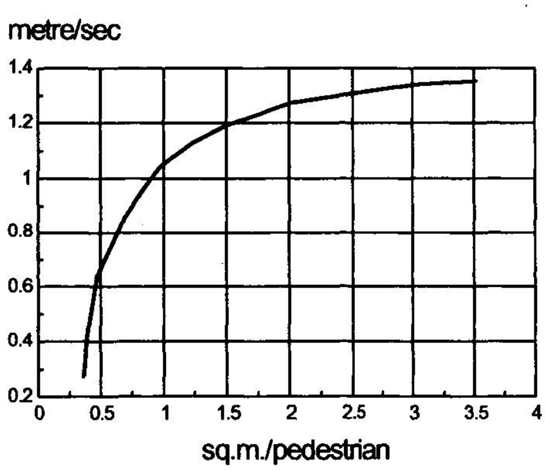


Fig.1. Pedestrian walking speeds. (Taken from Fruin.)

The work of Fruin [4] provides many of the benchmarks for pedestrian movement. The simplest of starting points is the free flow walking speed which Fruin obtained from surveys of 1000 non baggage carrying pedestrians, 1.37 m/sec for males and 1.29 m/sec for females. Tanaboriboon [14] obtained a mean value for Singaporean men of 1.32 m/sec and for women 1.15m/sec. These differences in such a basic parameter are an indication of the difficulty in examining the characterisitics of crowd flow from a general viewpoint. Cunningham and Cullen [3] in work relating to London Underground point to the volume of work that the measurement of pedestrian characteristics has produced and the associated difficulties. Crowd density influences the velocity of the individual within the crowd and numerous authors have examined the relationship. Fig.1 taken from Fruin [4] illustrates an observed relationship between density and velocity, experimental scatter exceeded ±10%. The primary interest concerns the flow rate of the mass as opposed to the velocity of an individual and this is illustrated in Fig.2. Also shown in Fig.2 are results presented by Ando [1]. The shift in Fig.2 emphasises the particular nature of any empirical study. The mean walking speed of Singaporeans is 74 ped/m/min., relatively slower than that of his American counterpart. Nevertheless the Singaporean maximum flow rate is 89 ped/m/min which is higher than the 81 ped/m/min and 78 ped/m/min obtained in the U.S. and Britain respectively.

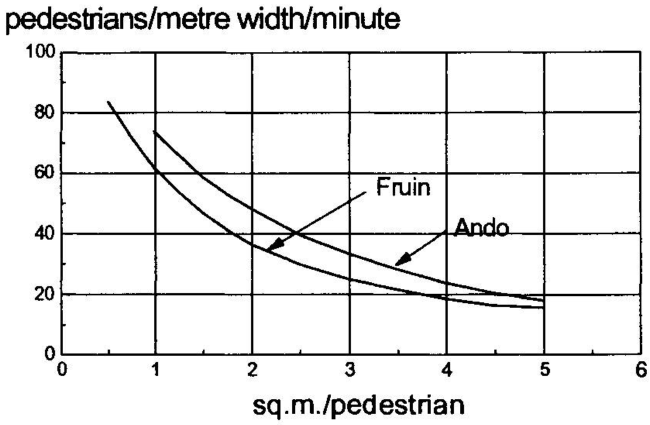


Fig.2. Pedestrian flow rates.

Considerable variations in these measured values occur without crossing international boundaries; Hoel [5] measured pedestrian walking speeds in the U.S. at 88 ped/m/min. A 15 second surge into a civil defense shelter was measured as equivalent to 146 /m/min., with a 5 minute interval reaching 105/m/min. Peak values for marching soldiers of 157 /m/min., have been obtained.

Pedestrian flow rates impact on the engineer,architect and emergency planner through design codes that specify allowable flow rates through varying exit widths. These in conjunction with evacuation times result in necessary component and aggregrate exit widths in any facility. The Guide to Safety at Sportsgrounds [7] gives maximum flow rates and assumes that the movement is through an exit width of at least 1.1 metres (a double unit width). From stands and all stairways a flowrate of 40 persons/minute per unit of exit width (550 mm) is required. From terraces and the ground generally a flow rate of 60 persons per unit of exit width should be used. The Guide to Fire Precautions in Existing Places of Entertainment and Like Premises [6] states that in crowded conditions a file of people moving through and opening will occupy a space of about 525 mm in width (unit of exit width). Furthermore people will move through that space at a rate of about 40 persons per minute per unit of exit width. It is questionable whether the concept of calculating exit widths in multiples of a given dimension can be considered valid above 2 units wide. Above this regular patterns of formation become blurred. It is against this background that there has been a development in recent years of a system based on increments of unit width rather than whole units. It is recommended that in places of entertainment the lowest incremental width to be used should be 75 mm which would allow for up to 15 persons where the maximum caluculated evacuation time is 2.5 minutes; each exit dealt with seperately. BS 5588, Fire precautions in the Design, Construction and Use of Buildings [2] gives allowable capacities in terms of exit widths varying from 800 mm up to 1800 mm. Above 1100 mm the capacity:width relationship is linear. A 1500 mm exit width is required for 300 people. If a flow rate of 80 persons/m/min., is assumed the evacuation time would be 2.5 minutes. An exit width of 5mm/person gives an exit time of 2.5 min. This is also the value given in NFPA 101 [9].

3. MODELLING OF CROWD FLOW.

Kendik [8] classifies current models evolving from people movement:

1. Flow models based on the carrying capacity of independent egress-way components or the unit exit-width concept.
2. Flow models based on empirical studies of crowd movement.
3. Network optimization models.
4. Computer simulation models.

The first of these reduces the problem to a simple aggregation. The second approach has been adopted by a number of authors. Polus [10] uses both one- and three-regime linear models to fit relationships between pedestrian speed and density. The third approach was used by Selem and Al-Rabeh [12] who present a model concerning a site at Mecca that accommodates 750000 pilgrims. The pilgrims cross a bridge and stop on three occasions, each time in the vicinity of a pillar in order to perform a religious rite. The bridge is in essence a corridor with three obstructions where the pilgrims halt. The area was broken down into activity zones the geometry of these was established using aerial photography. Predetermined safe crowd densities were set for each zone and an optimisation procedure was adopted to establish a safe flow onto the bridge. The demand interval spanned 5 hours; the model indicated that in order to avoid congestion that would exceed safety limits an 8 hour interval was necessary. Different examples of the fourth category are to be found in the Engineering for Crowd Safety conference proceedings [13].

4. PRESENT WORK.

Savage [11] clearly demonstrates the practicality of computer simulation in examining a number of problems relating to continua that are aptly described using hard particle models. In his granular flows, knowing the positions and velocities of all the particles, one searches through the particle list to determine the next particle pair that will collide; knowing the law that descibes the collision the collision is implemented to determine the post collisional velocities and directions of the colliding particle pair and so on. The driving forces included gravity, wind and ocean currents.

In the problem to be considered here each pedestrian provides the driving force; the avoidance of collisions in combination with available spaces determines the pattern of movements. In this application the model describes a two-dimensional unidirectional flow of a variable density crowd randomly distributed in an Observation Area which is a rectangle of length L and width W. The crowd flow is parallel to the length L, simulating a corridor situation. The number of people in the Observation Area determines the density. This number of people will always be present in the Observation Area since it is bounded by periodic boundaries; as an individual passes through the upstream boundary reentry occurs at the same location on the downstream boundary with the same speed. For the work presented here the length L, the separation between periodic boundaries, was set to 12.19 m (40 ft) while the width and densities were varied from 1.22 - 3.05 m (4 - 10 feet) and 5 - 55% respectively. However, the length can be varied as required. An individual's Resident Area is represented by an octagon enclosing a circle of diameter 610 mm. The Observation Area has a mesh 30.5 mm square, only one individual's Resident Area may occupy a node in the mesh. In addition all individuals have a Movement Area that is defined by an octagon enclosing a circle of 1220 mm diameter. The simulation is initiated by the random placement of individuals within the Observation Area. The velocity assigned to individuals follows a Normal Distribution with the user defined mean and standard deviation. The assigned speed is the maximum speed with which that individual can move. However, it is possible to model a disabled or an energetic individual by assigning individuals a very low or very high speed respectively.
The Movement Area enables each individual to move forward with a stride length of 610 mm. The preferred direction is straight forward, but if this is not possible then the individual randomly chooses to move either left or right. Lateral movement left or right is restricted to 305 mm. Motion forward is achieved by scanning for space that allows a full length stride with a corresponding space for the second stride. If space is available for two strides, the individual moves forward by one stride. If space is only available for the first stride, the individual still moves forward, the preferred direction being straight ahead. If movement by one stride is not possible, the whole sequence is repeated for reduced stride. The reduction being 30.5 mm each time (the nodal spacing) till either movement is possible or zero foot stride is reached which means no motion is possible. An individual will always

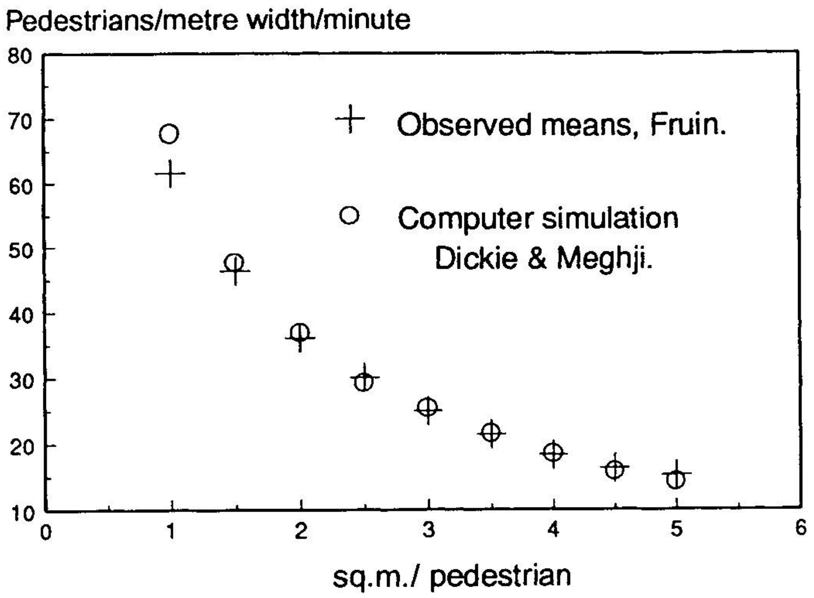


Fig.3. Comparison of observation with simulation.

advance as far forward as possible. The movement starts with the individual with the highest speed. The time for next normal stride is computed for each individual and is compared with the total simulation time to determine the next individual motion. All individuals in the Observation Area will try to move with their assigned maximum speed during the whole of simulation process. The simulation is run for about 500 seconds and the results are then averaged.

Fig.3 illustrates a comparison with the observed results of Fruin [4]. The results concern a crowd possessing a walking speed distribution that has a mean of 1.31 m/sec and a distribution of .152 m/sec. At higher flow rates (>90) the model will produce the same falling flow rate that is observed in practice.The correlation between the observed results and those obtained from the model is good. The ability of a pedestrian to alter his or her gait is recognised by the model. In addition variation of anthropometric data is possible.The model has been used to examine certain factors that will influence crowd flow. A summary of the results for crowd densities that give approximately one person/ m^2 is contained in Table 1.

Case	No.of Ped.	Velocity m/sec	Deviation m/sec	Flow Ped/m/min	Corridor width (m)	Comment
1	40	1.31	0.061	81	3.05	
2	40	1.40	0.061	87	3.05	
3	40	1.31	0.152	77	3.05	
4	40	1.40	0.152	87	3.05	
5	39	1.31	0.061	82	3.05	+1 at 1.83 m/sec
6	39	1.31	0.061	79	3.05	+1 at 0.61 m/sec
7	35	1.31	0.061	70	3.05	+5 at 0.61 m/sec
8	16	1.31	0.061	81	1.22	
9	20	1.31	0.061	81	1.52	
10	24	1.31	0.061	81	1.83	
11	15	1.31	0.061	43	1.22	+1 at 0.61 m/sec
12	19	1.31	0.061	71	1.52	+1 at 0.61 m/sec
13	23	1.31	0.061	76	1.83	+1 at 0.61 m/sec

Table 1.

Case 1 serves as a reference value and concerns a flow level of 81 pedestrians/ metre width /minute, similar to the values adopted by all design codes. It should be borne in mind that the velocity given in column 3 is not the mean velocity of the crowd, it is the mean of each individual's velocity potential Due to lateral movements and interferences in stride patterns the mean velocity of the flow is the character of an audience to be taken into account. A crowd leaving a football match will be predominantly composed of young men who will walk with speeds that are higher and lie in a narrow band than an audience leaving a theatre. The influence of a slow individual, Case 6, is not significant in the larger crowd. One person in forty is 2.5%, if the level is increased to 12.5%,Case 7, the decrease in flow is more marked. Two unit of exit widths referred to in numerous codes are equivalent to 1.1 m. Case 12 relates to an exit width of 1.22 m and clearly a slow individual will significantly impede the flow. The reduction for an exit width of 1.52 also represents a significant departure from code values. In flows of this density and over a length of 10 m a pedestrian might expect to change his line of forward movement possibly once. Case 5 concerns an individual who wishes to move at a rapid walk. The model shows that the speed of this individual's walk requires that he or she will be making lateral adjustments at a rate of one per metre, increasing the possibility of collisions.

5. CONCLUSION.

A computational model is presented that enables crowd flow to be examined and the model is shown to agree well with field data. The density of the crowd and the characteristics of individuals who make up the crowd can be varied. The impact of slowly and rapidly moving individuals is considered and the results have implications with regard to exit widths assumed in commonly used codes.

6. REFERENCES.

1. ANDO,K. et al. Forecasting the flow of people, (in Japanese), Railway Research Review, **45**, 1988, pp 8 - 14.
2. BRITISH STANDARD INSTITUTE. Fire Precautions in the Design, Construction and Use of Buildings. Part 6:Code of Practice for Places of Assembly. BS5588:1991.
3. CUNNINGHAM,P.P. and CULLEN,D.A. Pedestrian flow data collection and analysis. Proc. Instn.Civ.Engrs, Transp., **100**, Feb.1993, pp 59-69.
4. FRUIN, J.J., Pedestrian Planning and Design, Elevator World, Mobile, Alabama, 1987.
5. HOEL,L.A., Pedestrian Travel rates in Central Business District. Traffic Engineering, January 1968, pp 10 - 13.
6. HOME OFFICE. Guide to Fire Precautions in Existing Places of Entertainment and Like Premises, HMSO, London, 1990.
7. HOME OFFICE. Guide to Safety at Sportsgrounds, HMSO, London 1990.
8. KENDIK,E. Die Berechnung der Personenströme als grundlage für die Bemessung von Gehwegen in Gebäuden und um Gebäude. PhD dissertation, Technical University of Vienna.
9. NATIONAL FIRE PROTECTION ASSOCIATION. Life Safety Code. ANSI/NFPA 101, 1991.
10. POLUS,A. et al. Pedestrian Level of Service. Journal of Transportation Engineering, ASCE, **109**, No.1,1983.
11. SAVAGE,S.B. Gravity flow of cohesionless granular materials in chutes and channels. J.Fluid Mech., **92**, 53-96, 1979.
12. SELIM,S.Z. and AL-RABEH. On the modelling of pedestrian flow on Jamarat Bridge. Transportation Science, **25**, 1991, pp 257-263.
13. SMITH,R.A. and DICKIE,J.F., (Editors). Engineering for Crowd Safety. Elsevier, Amsterdam,1993.
14. TANABORIBOON Y., et al. Pedestrian characterisitics study in Singapore. Journal of Transportation Engineering, ASCE, **112**, No.3,1986.
15. TEMPLER J., The Staircase, MIT Press, Cambridge, Massachusetts,1992.

Crowd Actions and Grandstands

Effet des foules sur les tribunes

Einwirkung von Menschenmassen auf Tribünen

Brian R. ELLIS
Structural Engineer
Bldg Research Establ.
Watford, UK

B.R. Ellis graduated at the Univ. of Nottingham before he joined BRE in 1974. He is a chartered structural engineer and involved with the measurement of the behaviour of prototype structures and the use of these measurements for improving numerical models.

Tianjian JI
Structural Engineer
Bldg Research Establ.
Watford, UK

Tianjian Ji joined the Dynamic Performance Section after working at the Harbin Architectural and Civil Engineering Inst. China Academy of Building Research and at the Univ. of Birmingham. He is a specialist in structural dynamics and numerical modelling.

John D. LITTLER
Structural Engineer
Bldg Research Establ.
Watford, UK

John D. Littler joined BRE in 1974 and obtained his PhD in Structural Engineering from Univ. College London in 1991. He is a specialist in experimental measurements and the response of structures to wind loading.

SUMMARY

This paper deals with the response of grandstands to dynamic loads generated by crowds. It considers the available guidance for design and the relevant findings of current research work. The dynamic loads are examined in terms of intensity, frequency range, attenuation due to crowd effects and numerical modelling. Then the interaction between crowds and structures is considered and the results are presented. The findings from a number of site tests on grandstands are given and main points discussed along with an indication of where further work is required.

RÉSUMÉ

L'article traite de la réaction des tribunes sous charge dynamique due aux spectateurs. Il expose les directives d'étude disponibles et les résultats correspondants des travaux de recherche actuels. Il examine les effets dynamiques sous forme d'intensité, plage de fréquences, réduction due aux effets de foule et modèles numériques. Il compare leurs interactions avec la structure et présente les résultats fournis par des essais in situ sur des tribunes. Il récapitule l'ensemble des effets et propose des recherches futures.

ZUSAMMENFASSUNG

Der Beitrag behandelt die Reaktion von Tribünenbauten auf die dynamische Belastung durch Menschenmengen. Er berücksichtigt die verfügbaren Entwurfsrichtlinien und Ergebnisse der gegenwärtigen Forschungsarbeit. Die dynamischen Einwirkungen werden hinsichtlich Intensität, Frequenzbereich, Abminderung infolge der Wirkung der Menschenmenge und numerischer Modellbildung untersucht. Hernach werden ihre Wechselwirkungen mit dem Tragwerk einbezogen und die Ergebnisse aus Feldversuchen an Tribünen angeführt. In einer Rekapitulation der Haupteinflüsse wird Ausblick auf zukünftige Arbeiten gegeben.

1. INTRODUCTION

The response of temporary grandstands to dynamic loads is currently considered to be an important safety issue and this has been emphasised by the collapse of part of a temporary stand at Bastia, in Corsica, in May 1992, which resulted in 13 dead and 1300 injured spectators. This paper looks at many aspects of this problem, including the available guidance for design and the relevant findings of current research work at the Building Research Establishment (BRE). It considers the dynamic loads which can be produced by crowds and how crowds interact with structures. It also discusses the measurements taken by BRE on a range of grandstands and the preliminary findings from these tests.

Within the UK, an engineer who was given the task of designing a temporary grandstand, would probably first examine the UK loading code [1] to see what guidance was given on dynamic loads, but would find the statement 'this does not allow for the dynamic loads due to crowds'. Further investigations would lead him to the ISE publication on this topic [2]. This document discusses the 'natural frequency' of a structure (presumably meaning the fundamental vertical natural frequency) and the need for it to be above 4 Hz so as to avoid resonance from rhythmic events involving a group of people, the most applicable range being 1½ to 3 Hz. It is also noted that in the case of jumping, the periodic forces can create significant dynamic loading at double the rhythmic frequency up to 6 Hz. However, the document is somewhat limited and provides little clear guidance for the designer and does not differentiate between sway and vertical loads, which is actually very important.

Examination of the CEB guide on vibration problems [3] provides more information about lateral swaying of audiences. This publication suggests a lower bound fundamental frequency of 2.5 Hz for sway motion of spectator galleries, and 3.4 and 6.5 Hz for vertical motions for 'soft' and 'hard' pop concerts respectively. This latter point, which considers different design loads for different types of event, is an important issue and is discussed later.

2. CROWD ACTIONS - DYNAMIC LOADS

A densely packed crowd will produce significant loads with both static and dynamic components. If the crowd movement is not co-ordinated then the dynamic component is likely to be much smaller than the static component; however there are certain types of co-ordinated movement where the dynamic component is larger than the static component and these should be considered. Perhaps the worst case is when the crowd jumps in time to music. The music serving to co-ordinate the crowd and the jumping providing significantly higher loads than the equivalent static load of the crowd.

A further factor to consider is that of resonance. If the frequency of the dynamic load occurred at a natural frequency of the structure on which it was imposed, a resonant situation would arise whereby the response would be amplified greatly. Hence it can be appreciated that a significant dynamic load occurring at a natural frequency of a structure can induce excessive vibrations, therefore it is a situation to be avoided.

When considering loads it is also important to consider direction because vertical or sway loads are not only different in magnitude but they are also different in frequency content. For temporary grandstands the primary interest is for sway loads whereas for dance floors and cantilevered grandstands the vertical loads are important.

2.1 Intensity

With a densely packed crowd there may be up to six people per square metre, although on occasions higher densities have been observed at particular events. Six people of average weight equates to approximately 4.8 kN/m^2, which is slightly below the UK design load of 5.0 kN/m^2. When the crowd are seated the density reduces and 4.0 kN/m^2 is often used in design.

The dynamic loads generated by a crowd are dependent upon the activity being undertaken by the crowd. If the worst case is considered, which is when an individual is jumping, then the load can be evaluated. Jumping creates a load at the jumping frequency and at whole number multiples of that frequency. This is discussed in detail in ref. (4) and the following table is extracted from that reference.

Activity	Contact Ratio	Dynamic load factors			
	α	1	2	3	4
Pedestrian movement Low impact aerobics	2/3	1.29	0.16	0.13	0.04
Rhythmic exercises High impact aerobics	1/2	1.57	0.67	0.00	0.13
Normal jumping	1/3	1.80	1.29	0.67	0.16
High jumping	1/4	1.89	1.57	1.13	0.67

Table 1 Dynamic load factors for various activities involving jumping

The factors given in the table require some explanation. The contact ratio is the ratio of time when the jumper is on the ground to the time for one cycle of the jump, thus a contact ratio of 1 would mean that the person was always in contact with the ground. The load can be split into its Fourier components for the jump frequency and whole number multiples of it, the multiples 1, 2, 3 and 4 being shown in the table. The dynamic load factors are the amplitude of the harmonic term of the Fourier component. For example for the high impact aerobics, where α=1/2, the first dynamic load factor (which occurs at the jump frequency) is 1.57. The dynamic load factor shows the load amplitude in addition to the static load which is defined as 1.0. Thus it can be appreciated that the dynamic loads can exceed the static loads and that significant loads can occur at whole number multiples of the jump frequency, which is important when possible resonances are considered.

Jumping is likely to produce the largest vertical loads, but horizontal loads are important for the sway vibrations of a structure. The information on sway loads is rather sparse and this subject has not yet been investigated by BRE, the best current information being found in the CEB guide [3] which suggests a load factor of 0.3 for sway at 0.6 Hz.

2.2 Frequency

With dynamic loading the ratio of load frequency to the fundamental structural frequency is important due to the possibility of resonance. For example, if a person was jumping at the fundamental frequency of a floor which had a damping value of 2% critical, the amplification due to resonance could be up to 25 times. For jumping the frequency range over which a person can jump is 1.5 to 3.5 Hz, although there is reason to believe that for a crowd the upper frequency is 2.8 Hz. The fact that for jumping, significant energy is generated at whole number multiples of the jump frequency, leads on to a rule which has been suggested, that to avoid resonance a fundamental frequency of a structure should be above three times the dance frequency. This figure actually relates to safety where displacement or stresses are of concern and is not applicable for accelerations which may be a serviceability issue.

For sway vibrations information is again available from the CEB guide which suggests the load is mainly at slow rhythms between 0.8 to 1.4 Hz, with the lateral body swaying at half the beat frequency giving a range of 0.4 to 0.7 Hz. The guide suggests a lower bound fundamental frequency of 2.5 Hz for sway motion.

2.3 Crowd Effects

In section 2.1 the maximum crowd density and the loads produced by individuals were mentioned, but when considering the loads produced by crowds there are one or two factors which should be considered. First there is the interaction between crowd and structure which can be important and this is considered in the next section. Secondly there is the expectation that if a crowd all tried to jump at the same frequency, which may be the case for some dances, then there is a likelihood that their co-ordination will not be perfect and there will be a resulting attenuation of the overall load. The imperfections in co-ordination may be due either to individuals not dancing at exactly the beat frequency, which may be more common at the extremes of the frequency range, or due to phase differences between individuals. A theoretical study of the attenuation due to phase differences is given in ref. [5] and suggests a likely attenuation of approximately 1/3 for a large crowd. However, this is primarily for vertical loads and horizontal loads have not yet been studied.

2.4 Modelling of dynamic loads

It is relatively simple to model sway loads for individuals and models for jumping loads are also available [6]. Given the number of people involved, the frequency of the co-ordinated movement and the crowd effect, the overall load can be determined. To simplify the dynamic calculations, it is possible to consider just the fundamental mode of vibration. The actual jumping load can be expressed as the sum of the Fourier terms in which the amplitudes of the terms are shown in the previous table.

In order to calculate response, it is necessary to evaluate the fundamental structural characteristics (i.e. natural frequency, damping, mode shape and modal stiffness), and for some structures this may neither be straightforward nor accurate. The best mechanism for providing accurate estimates of structural characteristics is a combination of experience from previous analysis plus feedback from field tests. Besides the basic structural characteristics there is the interaction between crowd and structure which is discussed in the following section.

3. CROWD ACTIONS - HUMAN BODY EFFECT

For a number of important vibration problems, the interaction between a group of people and a structure is significant and evaluating this interaction is critical if overall behaviour is to be assessed; but, at present, there are no authoritative studies on this subject. The current general understanding is demonstrated by a Canadian Code [7] which treats the human body as a 'dead' mass on the structure, and this results in a simple reduction of the natural frequency of the structure. Measurements on a large cantilevered stand by the authors [8] indicated that the involvement of spectators changed the dynamic characteristics of the stand. For the empty stand a well defined fundamental mode was recorded, but when the crowd were present two modes to either side of the original frequency were observed. This suggested that the human body, or a group of people, acts as a spring-mass-damper system, rather than a 'dead' mass.

3.1 Laboratory tests

Following the observations on the cantilevered stand a series of simple experiments were undertaken in the laboratory. The first involved taking measurements on a small simply supported beam. The frequency of the beam was measured at 18.7 Hz. When a person stood or sat on the beam, the frequency increased and the damping value increased significantly. When a rigid mass equivalent to that of the person was placed on the beam, the beam frequency decreased and the damping value remained unchanged. This indicated that the person acted as an additional mass-spring-damper system, and it was also noted that the human spring stiffness varies with posture. The tests, and subsequent analysis suggested that the human frequencies were in the range 8 - 10 Hz when standing and 4 - 6 Hz when seated.

For the case where people were jumping, stamping and running on the spot, their mass was not vibrating with the beam and it was found that the human involvement was as a load only, with the characteristics of the beam measured during the tests being the same as the bare beam. Hence for calculation of an event where people are jumping the characteristics of the bare structure should be used.

3.2 Human-structure vibrations

Complementary theoretical work has been developed at BRE examining several aspects including the theory of human-structure vibrations, floor vibrations induced by dance type loads and the indirect measurement of the human whole-body frequency.

If the beam and the person are each considered to be one degree-of-freedom systems, the person standing on the beam will provide a two degree-of-freedom system. The frequencies of the beam and of the person are always between those of the two frequencies of the person-beam system. With the experiment where the measured frequency of the beam seemed to increase, only one of the two modes of vibration was being observed; the other mode, which occurs at a lower frequency, was not observed. If the situation arises where the structure and human frequencies are similar, then both modes of the combined system will be seen, which has both been seen for a large cantilevered grandstand and has been verified experimentally in the laboratory. If the condition occurs where the structural frequency is below the human frequency, the observed structural response for the combined system appears at a lower frequency than that of the bare structure.

The development of the theoretical methods of modelling human-structure vibrations also leads to methods of measuring the frequencies of crowds or individuals and calculating system behaviour. To date work has not been undertaken on sway vibrations, but the required experimental procedures are clear and the mathematical models used for vertical vibrations should be valid. Sway tests should be conducted by BRE in 1994.

4. SITE EXPERIMENTS ON GRANDSTANDS

BRE have examined a number of temporary grandstands and two permanent cantilevered stands in order to get some practical experience with these types of structure. It is only by obtaining such experience that the real problems and solutions can be identified. Also there are some characteristics, e.g. damping, which cannot be predicted, but where experimental values are required for any calculation of dynamic behaviour; however, these values are not yet available for a wide range of structures.

For each structure, BRE adopted the following experimental procedure:

1. Test the structure when empty to identify the system behaviour and define the fundamental mode in each direction (vertical, sway and front-to-back).
2. Monitor the response of the structure as the spectators get seated, throughout the event and as the spectators leave.
3. Analyse 2. to see
   a. peak response
   b. frequency at which peak response occurs
   c. changes in structural (system) characteristics due to crowd

Theoretically it is possible to derive modal loads from measured response knowing the system characteristics but this is only viable on relatively simple systems.

A range of structures has been examined for various types of event, but in this paper only a few of the findings can be mentioned. For the two cantilevered grandstands, one had a fundamental frequency approximately equal to the crowd frequency, hence two frequencies were observed with the crowd present. The other had a frequency much less than the crowd frequency hence when the crowd was present a lower frequency was recorded in comparison with the empty condition. Although one of the cantilevered stands had a relatively low fundamental frequency it didn't suffer significant vibrations because the large crowd did not have any co-ordinated actions.

For the temporary grandstands, the fundamental vertical frequencies were sufficiently high to avoid safety problems from dynamic loading, however, the frequency of the fundamental sway modes were often very low, especially for the taller systems. For the lower frequency modes changes were noted in the frequencies when crowds were present, the observed changes supporting the human-structure model. For a lot of events the vibrations, were relatively low level, with the wind providing a significant vibration source for outdoor events. However, for pop concerts where stamping and jumping was common, response at the jumping frequency and whole number multiples thereof was observed for vertical vibrations and a corresponding pattern was seen for horizontal vibrations. This latter point is of particular interest as it shows that vertical loading is being channelled into horizontal vibrations, and hence provides a mechanism for producing significant vibrations at higher frequencies than simple sway vibrations.

5. DISCUSSION

To date the experimental work has identified a number of points. For temporary grandstands the sway frequencies are relatively low, suggesting that resonance at the basic load frequency is possible, however this is only likely to happen at events like pop concerts where crowds respond to music. This is likely to be a problem for taller grandstands. For temporary grandstands the vertical frequencies are usually quite high hence vertical response is likely to be adequate. For cantilevered stands or dance floors, vertical motion is likely to be of concern, but again only for certain events. As the dynamic loads generated by jumping are far greater than for non co-ordinated movements, it begets the question as to whether it is reasonable to introduce classifications with different loads for grandstands when different types of crowd behaviour can be guaranteed. However, significant loading cases cannot be attributed solely to pop concerts, for example in Brazil football crowds tend to sing and dance to their favourite songs when goals are scored, hence compounding the problems which have been noted in the Maracana stadium.

The common method of avoiding resonance, and the potential problems which it introduces, is to set a minimum fundamental frequency (in the appropriate direction) above the range of expected excitation frequencies. It should be noted that this is only reasonable when considering displacements, and cannot be justified for accelerations; the reasons for this are given in ref. [6]. Two points should be borne in mind when considering a minimum frequency. First, the interaction between crowd and structure will affect the frequency, and second, the question again arises as to whether different types of event justify different frequency limits.

For vertical loads the frequency range and likely load amplitudes are known, albeit further work is required on the crowd effect, which models the reduction in load due to a lack of synchronisation of a large crowd. For sway loads more work is required on estimating both load amplitude and frequency range, and on the transference of vertical loads into sway motion. For human structure interaction, work is required on modelling human whole body motion, both for sway motion and for evaluating dynamic effects. For grandstands, tests to monitor the response to co-ordinated jumping should be sought and further measured values of damping are required.

REFERENCES

1. BS6399: Part 1: Loadings for buildings, 1984.
2. Institution of Structural Engineers. Safety consideration for the design and erection of demountable grandstands. May 1989
3. CEB Bulletin D'information 209. Vibration problems in structures - (section 1.4). Aug. 1991
4. ELLIS B. R. and JI T. Floor vibration induced by dance type loads - verification. ". Structural Engineer, Vol. 72, No 3, 1 February 1994, pp 45-50.
5. JI T. and ELLIS B. R. Evaluation of dynamic crowd effects for dance type loads. Colloquium on Structural Serviceability of Buildings, Goteborg, June 1993.
6. JI T. and ELLIS B. R. Floor response induced by dance type loads -- theory, Structural Engineer, Vol. 72, No 3, 1 February 1994, pp 37-44.
7. National Building Code of Canada 1985, National Research Council of Canada, Ottawa, Canada.
8. ELLIS B. R. and JI T. Human-structure vibrations. *To be submitted for publication to the ICE.*

Dynamic Loading of Feyenoord Stadium during pop concerts

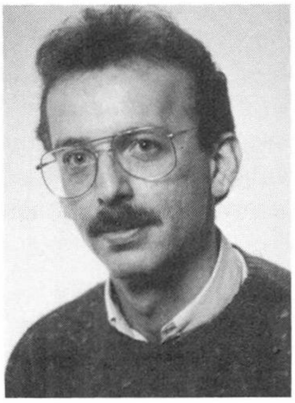
Sollicitation dynamique du stade de Feyenoord lors de concerts

Dynamische Belastung des Feyenoord-Stadiums bei Pop-Konzerten

Piet VAN STAALDUINEN
Civil Eng.
TNO-Building & Constr. Res.
Delft, The Netherlands

Piet Van Staalduinen, born 1963, got his civil engineering degree at Delft Univ. of Technology, the Netherlands. Since 1986 he is affiliated with TNO as a project engineer in structural dynamics within the Department of Structural Engineering.

Wim COURAGE
Research Project Eng.
TNO-Building & Constr. Res.
Delft, The Netherlands



Wim Courage, born 1961, got his mechanical engineering degree at the Univ. of Eindhoven, The Netherlands, where he also received his PhD. Since 1990 he is affiliated with TNO as research project engineer in structural dynamics and reliability studies within the Department of Structural Engineering.

SUMMARY

Since 1980, the Feyenoord football stadium is also used as a venue for pop concerts. During the concerts large vibrations sometimes appear in the structure as a result of dynamic crowd loading. During pop concerts the structure is being monitored. With the monitored data a direct feedback can be given to the sound and video director. Based on this feedback, they interfere with sound and video and can thus limit the vibrations. With this system experience has been gained during 25 concerts, covering a period of 5 years.

RÉSUMÉ

Depuis 1980 le stade de football de Feyenoord sert aussi pour les concerts de musique populaire. D'importantes vibrations des structures porteuses furent constatées au cours de ces concerts, par suite de l'action dynamique des mouvements de foule. Dès lors, un système de mesure surveille la structure et les données relevées sont directement transmises aux responsables son et lumière. Ceux-ci peuvent réduire les performances acoustiques et ainsi limiter les vibrations. Le système a été expérimenté pendant 5 ans et 25 concerts.

ZUSAMMENFASSUNG

Das Feyenoord Fussballstadion wird seit 1980 auch für Pop-Konzerte benutzt. Mitunter machen sich grosse Tragwerksschwingungen als Folge dynamischer Einwirkung von Menschenmassen bemerkbar. Das Tragwerk wird jetzt während Pop-Konzerten messtechnisch überwacht und die Messdaten direkt den Licht- und Ton-Meister überspielt. Letztere können das Klangvolumen dämpfen und dadurch die Schwingungen begrenzen. Es wurden während fünf Jahren bei 25 Konzerten Erfahrungen gesammelt.

1. INTRODUCTION

The Feyenoord stadium had an original capacity of 61.000 people. The stadium consists of two rings that are supported by 120 steel framed trusses placed arond the pitch. The stands are cast-in-place concrete slabs. The second ring of the stadium cantilevers above the first ring in order to obtain a maximum sight on the pitch. The design of this stadium is special, since it gives an unrestricted view on the pitch from every seat of the stadium. Only a part of the second ring has a roof, that is also a cantilever structure. Figure 1 gives a schematic cross section over stands. As can be seen from figure 1, the second ring is as near to the pitch as the first ring, which also contributes to the good sight and gives this stadium some intimacy.

In the design self-weight, static crowd loading and wind load was accounted for. At the completion of the building stage in 1936, a static test loading was carried out by 1500 people. Only one of 120 trusses of the stadium was covered by this loading. Displacements of the first and second ring were recorded. Over the years it has become a well known phenomenon that a goal during a football game yields a well perceptable vibration in the stadium. However, at a football match, this vibration damps out rather quickly. Measurements indicated that the amplitude of the dynamic displacement at such an event, measured at the very extreme of the second ring, amounts to some 2 or 3 mm. In 1987 the stadium design calculations were reviewed on the basis of the vigilating building regulations in the Netherlands. This implied a static crowd loading of 4 kN/m^2 and a wind load having a dynamic pressure of approx. 900 N/m^2. Only minor structural modifications had to be made in order to meet these new requirements.

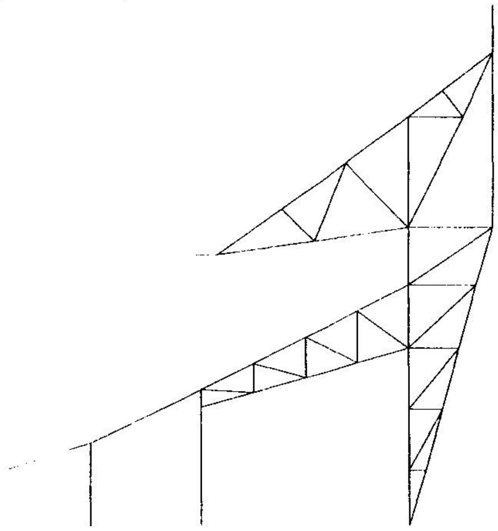


Fig. 1 2D Model of single truss

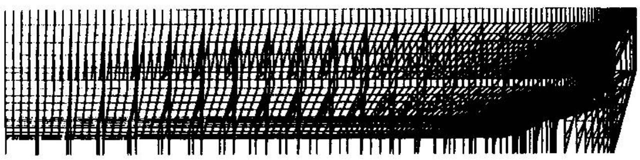


Fig. 2 3-D Model of a quarter of the stadium

2. DYNAMIC BEHAVIOUR DUE TO CROWD LOADING

From the calculations, it appears that the deflection of the second ring due to the static load of 4 kN/m^2 is approx. (25 mm). Such deflections clearly indicate the large flexibility of the structure. This flexibility originates from the special design principles that the architects adopted. An analysis of a single truss using the finite element method DIANA shows that the first three natural frequencies of a single truss are below 10 Hz. Also a quarter of the perimeter of the stadium (30 trusses) was modeled in order to investigate ring effects. Figure 2 shows the finite element model and results are summarized in Table 1.

frequency (Hz)			mode shape
calc[1]	calc[2]	meas	
1.58	2.02	2.3	predominant lateral sway of the second ring
3.65	-	4.5	predominant out of plane translation of the second ring
6.14	-	5.8	predominant vertical translation of the tip of the first ring

Table 1 Natural frequencies and mode-shapes of the stadium structure
[1]) analysis of single truss (2D model); [2]) analysis of a quarter of the perimeter (3D model)

In figure 3 the mode shapes of a single truss are shown. In 1982 vibrations measurements with just wind as excitation confirmed the existence of these natural frequencies. The estimated damping ratios (as a fraction of the critical damping) are approx. 0.07, 0.12 and 0.05 respectively. From the calculations and measurements it can be concluded that the additional stiffness of ring-shaped concrete slabs is significant.

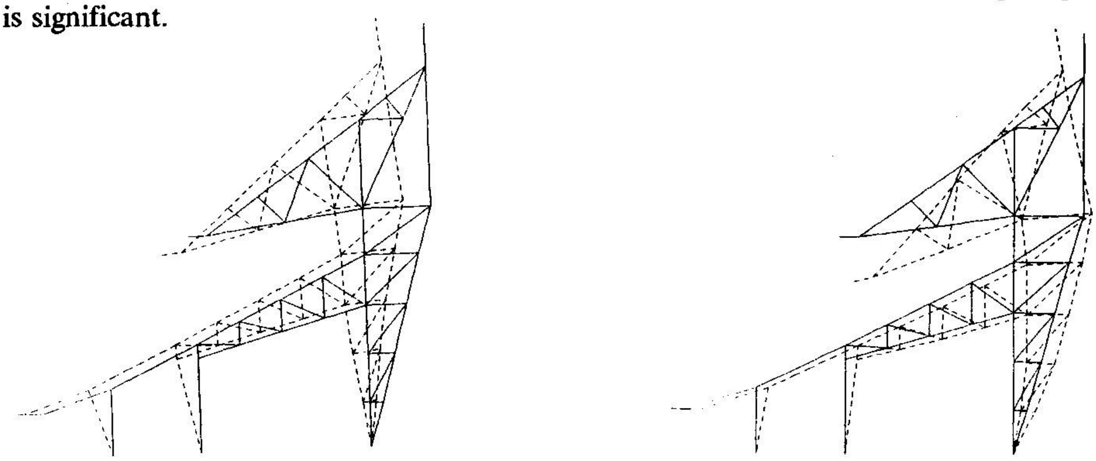


Fig. 3 First two mode shapes of a single truss

Dancing people can exert a significant dynamic loading at frequencies of around 2, 4 and 6 Hz. Indeed, at the first pop concerts that were organised in the stadium strong vibrations did occur. At the second ring the vibration intensity was such that some people got frightened. The city authorities responsible for building safety ordered an investigation into the extent and causes of these strong vibrations.

3. MODELS OF DYNAMIC CROWD LOADING

The main dynamic loading during pop concerts are due to dancing or bending of the knees, on the rhythm of the music. Different models for this loading have been proposed in literature, such as the sine model, and the triangular model. Since we deal with a periodic excitation, it can be developed into a Fourier series

$$F(t) = G[1 + \sum_n \alpha_n \sin(2\pi f_n t + \phi_n)]$$

where

G is the weight of the people, in N
α_n is the fourier coefficient for the n-th harmonic, normalized on G
f_n is the n-th harmonic frequency, in Hz
ϕ_n is the phase of the n-th harmonic, in rad

Table 2 gives a set of Fourier coefficients for different models with f_1 = 2 Hz as found in literature.

model	α_1	α_2	α_3	remarks
uniform model	1.65	0.83	-	(t_c /t = 0.33 after Wyatt [10])
sine model	1.78	1.26	0.63	(t_c /T = 0.34 after Eibl [4]
triangle model	1.62	0.81	0.18	(t_c /T = 0.5 after Gerasch [5])
measured	1,80	1.31	0.75	(t_c /T = 0.4, after Baumann [2])
measured	1,46	0.60	0.17	(N persons, after Embrahimpour [3])
measured	1.65	0.90	0.25	(1 person, after Allen [1])
measured	1.45	0.50	0.07	(8 persons, after Pernica [7])
measured	-	0.51	0.10	(building measurement, after Rebelo [8])

Table 2 Fourier coefficients for dynamic crowd loading

As shown by Pernica [7], the sine and triangle model appear to be conservative for the 2nd and 3rd harmonic, especially for groups of people. Probably small differences in dancing between individual people tend to decline these coefficients. The lower values for the 2nd and 3rd harmonic are confirmed by measurements in buildings reported by Rebelo [8]. The decline of the fourier coefficients for a higher number of people is also indicated by Kasperski [6], who introduces a coordination factor in order to account for this. For large groups, this factor is stated to be 0.5.

The data above show that for a purely static structure, the action effect due to dynamic crowd loading is 2 to 3 times the static crowd loading. The coincidence of forced and natural frequencies, as may well be the case in the Feyenoord stadium, will even increase this ratio due to resonance effects.

Under unfavourable conditions such as a strongly correlated dynamic loading and a coincidence with one of the natural frequencies, these theoretical considerations imply that dynamic crowd loading in the Feyenoord Stadium may lead to very large dynamic displacement and stress amplitudes. Such a dynamic response may be unacceptable both from the point of view of building safety and vibrational discomfort. The uncertainty in the dynamic response to pop concerts forced the city authorities in 1987 to withdraw the permit for pop concerts in the stadium. Only a limited permit was issued only for a few concerts to allow for measurements to be made.

4. MEASUREMENT OF THE DYNAMIC CROWD LOADING

In August 1987 additional measurements into the dynamic behaviour of the stadium were performed during the concert of Madonna. At approximately 1/4 of the perimeter of the second ring of the stadium the vertical acceleration was measured, see Figure 4. In addition to this, strains were measured at a number of critical elements in several trusses. The maximum amplitudes amount to 3 mm vertical and 2 mm horizontal. Accelerations reached peak values of 1,3 m/s^2.

Transfer functions were calculated between the deflections measured at different places along the second ring. From this, figure 4 shows the ratio of the displacement at 2 and 4 Hz along the second ring, together with the phase lag. Due to the fact that the sound arrives later at a greater distance, a considerable phase lag occurs. This leads to a kind of 'wave' in the structure.

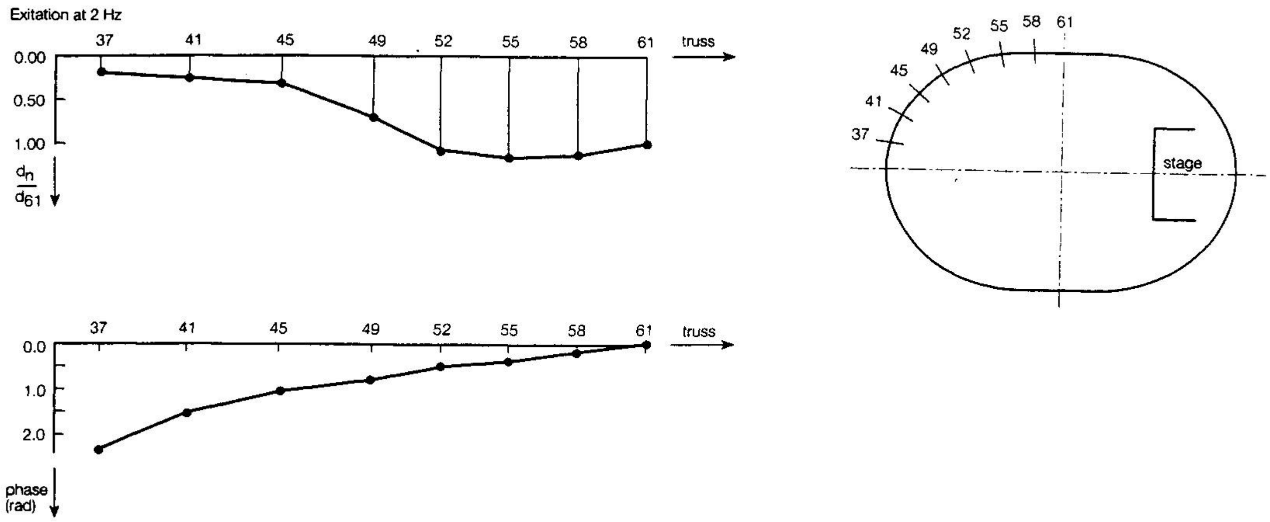


Fig. 4 Ratio of displacement along the perimeter of the stadium at 2 Hz

The static displacement of the 2nd ring is approx. 10 mm; at this concert the static crowd loading appeared to be 1.7 kN/m^2 and the maximum dynamic amplification 1.3. The relation between deflection and strain at 2 and 4 Hz differs from the static relation, indicating that vibration modes also play an important role. Especially the 2.5 Hz lateral sway induces a remarkably small strain in the main vertical truss.

5. MONITORING OF VIBRATIONS

In 1987 it was decided that additional measures must be taken. Structural modification appeared to be very difficult due to the specific design of the stadium. Also, the installation of dampers was not favourable due to costs and the uncertainty about their effectiveness. Therefore, the priority was set on a monitoring system with direct feedback to the pop concert, since this could be installed at short time and moderate cost.

The monitoring of dynamic effects caused by some 50000 people requires a dedicated system having a very small response time with regard to the feedback. Based on the extensive measurements in August 1987 five locations along the 2nd ring were selected. Here, transducers were installed for measuring the horizontal and vertical deflection of the second ring. During concerts, these displacements (both static and dynamic) are continuously measured and evaluated, using a PC-based measuring system.

The feedback consist of a warning system to the sound and video directors of the concert. At prescribed levels of vibration, starting at 4 mm the sound level has to be lowered stepwise until a complete close-down at 6 mm, which in practice means an allowable dynamic amplification of 1.6. At an early stage, video screens have to show a neutral view. Experience has learned that at the moment the sound is lowered and closed down, the coherent excitation by the crowd stops within a few seconds.

Ideally, a fully automatic system could have been installed, that makes its decision on the basis of the measured results and can lower or switch off the sound level automatically. Because of the sensitivity of such a system for possible disturbances in the measuring signals or otherwise and problems of acceptation by promoters, two human decision makers are part of the chain:

the operator of the measuring system (the system however will indicate what action must

indicated to the sound and video director),
the sound and video directors of the artist concerned.

An additional advantage is that a permanent communication channel between stadium authorities and sound and video director exists.

Contracts between stadium and promoters for organizing concerts imply these procedures as conditions. Furthermore, the City of Rotterdam based its permit for organizing pop concerts in the stadium on this system.

6. EXPERIENCE

As far as known, this kind of monitoring system has not been applied earlier in order to insure the structural safety of a stadium under dynamic loading. For this reason, some experiences gained at the operation of this system are discussed here.

All concerts in the Feyenoord stadium since 1988 have been run using this system. Among these are concerts by Bruce Springsteen, The Rolling Stones, Genesis, Guns 'n' Roses, U2 and Metallica. Approximately 1 million visitors were present in this 5 year period. Apart from small modifications and software updates, the basis of the system is still the same as originally designed.

Prior to concerts a meeting is set with stadium officials, the promoter, the tour director, the sound and video director and the people concerned with the monitoring. After any concert, the results are made available for city authorities. Many concerts could be run without interference in the concert from the point of view of vibrations. During some concerts the sound level had to be lowered in preparation for a the complete switch-off. So far, only at the Guns 'n' Roses concert in 1992 sound nearly had to be switched off. This implies that the dynamic amplification rarely exceeds 1.6 and that the value of the coordination factor will be lower than 0.5.

REFERENCES

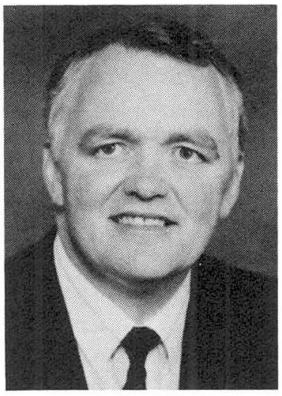
1. ALLEN, D.A., "Floor Vibration from Aerobics", Can.J. Civ. Eng. 17 (1990), 771-779.
2. BAUMANN, K., BACHMANN, H., "Durch Menschen verursachte dynamische Lasten und deren Auswirkungen auf Balkentragwerke", Bericht 7501-3 Institut für Baustatik und Konstruktion ETH Zürich, Mai, 1988.
3. EBRAMHIMPOUR, A., "Modelling spectator induced dynamic loads", Ph.D. thesis, University of Idaho, USA, 1987.
4. EIBL, J., RÖSCH, R., "Schwingungsprobleme an einem Fussballstadion", Bauingenieur, 65 (1990), 307-311.
5. GERASCH, W.J., "Reduzierung von beim Tanzen erzeugten Bauwerksschwingungen durch Schwingungstilger", Bauingenieur 65 (1990), 313 - 318.
6. KASPERSKI, M., NIEMANN, H.J., "Man induced vibration of a stand structure", in Structural Dynamics, T. Moan (Ed.), p. 977-983, Balkema, Rotterdam, 1993
7. PERNICA, G., "Dynamic Loads at a rock concert", Can. J. Civ.Eng. 10 (1983), 185-191.
8. QUAST, U., "Schwingungsverhalten der Tribünen des Volksparkstadions Hamburg", Beton- und Stahlbetonbau, 88 (1993), Heft 9, 233-236.
9. REBELLO, C., "Stochastische Modellierung menschenerzeugter Schwingungen", Massivbau Baustofftechnologie, Karlsruhe, Heft 17, Karlsruhe 1992
10. WYATT, T.A., "Floor excitation by rhythmic vertical jumping", Engineering Structures, 7 (1985), 208-220.

Design of Stadium Structures - A Safety First Approach

Projet des structures de stades sous l'angle de la sécurité

Der Entwurf von Stadien unter dem Primat der Sicherheit

Bill REID
Director
Thorburn Colquhoun
Glasgow, UK



Bill Reid, born 1945, graduated in Civil Engineering at Aberdeen University before joining the Consulting Engineering Practice Thorburn. B. Reid specialised in structure and foundation engineering and has a particular interest and a wide experience in Stadia Design. He has co-ordinated concept design work on 10 major stadia projects.

SUMMARY

The paper discusses the redevelopment work on Football Stadia which has taken place as a result of the requirements that spectators at the Major Stadia in Britain require to be seated prior to the beginning of the 1994-95 season. It also highlights where major deficiencies exist in the British Building Regulations and in Codes of Practice relating to the design process for Major Stadia.

RÉSUMÉ

L'article traite des travaux de réhabilitation des stades de football, à la suite des prescriptions devant entrer en vigueur en Angleterre pour la saison 1994-95 et impliquant que les installations les plus importantes puissent offrir aux spectateurs uniquement des places assises. L'auteur souligne en outre les insuffisances essentielles existant dans les prescriptions et normes techniques du bâtiment en vigueur dans ce pays, relatives au déroulement du projet des stades de grande capacité.

ZUSAMMENFASSUNG

Der Beitrag behandelt die Modernisierungsarbeiten an Fussballstadien, die aufgund der Forderung nötig wurden, dass für die Zuschauer in Grossbritanniens bis zur Saison 1994-95 grössere Stadien mit Sitzplätzen vorhanden sein müssen. Er weist ausserdem auf wesentliche Mängel in den britischen Bauvorschriften und Normen bezüglich des Ablaufs beim Entwurf grösserer Stadien hin.

1. INTRODUCTION

In Britain, it is Football stadia which generate, on a regular basis, the highest concentrations of people in a confined space. Since 1902 there have been 6 major tragedies at football grounds, each involving the loss of more than 25 lives and leaving many hundreds of individuals with serious physical damage and psychological impairment. There have been 10 major reports dealing with safety at football grounds since 1924, each making recommendations for additional measures to improve safety. Statistics from the disasters and a list of the reports are detailed in a paper by the author, UK Football Stadia – The Way Ahead [1].

The disaster at Hillsborough in 1989 with 95 deaths involved the largest loss of life. The report by Lord Justice Taylor which followed the disaster has also had the largest influence on changing the form of Britain's stadia.

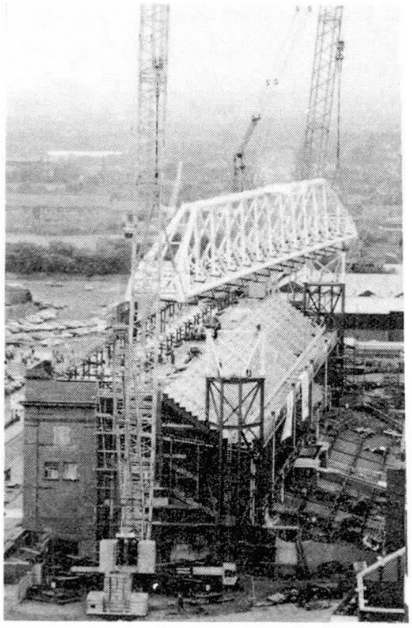
This paper reviews some of the projects completed post Hillsborough and discusses where design guidance and regulations may yet be deficient.

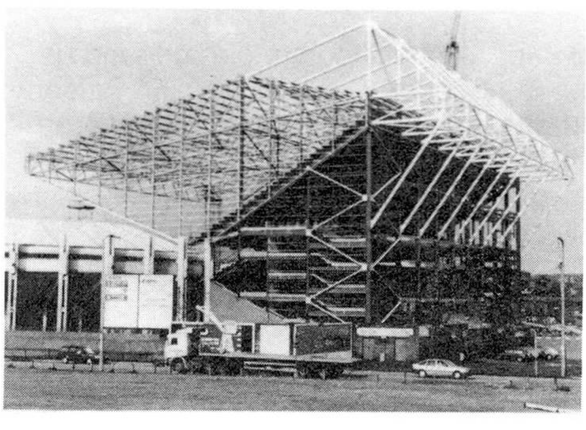
2. EXISTING STATE OF THE ART

All projects are different. Each has its own highlights and features of design or construction which are particular only to it. To illustrate this point the author has chosen 6 projects, constructed since 1991, each representing a major project and each illustrating a different approach to achieving the requirement for seated spectator accommodation.

Ibrox Stadium : Glasgow

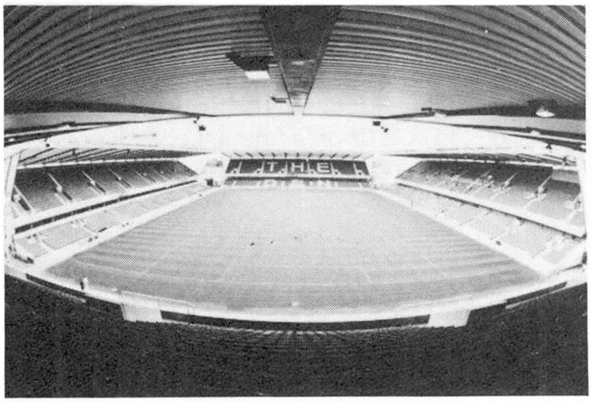
Ibrox Stadium was redeveloped in the early 1980s by the conversion of the standing terraces on the East, West and North sides of the pitch to seated accommodation for 25,000 spectators. In 1989 the Club decided to upgrade the South Stand accommodation by adding an additional seating deck above their existing Main Stand. The new deck, which affords column free viewing to the upper tier spectators, is covered by a new roof supported on a 145 metres clear span tubular steel girder. This is the longest span stadium girder of its type in Britain. The plate opposite shows lifting of the roof girder over Ibrox Main Stand.





Elland Road Stadium : Leeds

While Ibrox Main Stand Girder is the longest "goalpost" type girder in Britain, the longest cantilever structure is currently at Elland Road, Leeds. This structure has a clear cantilever roof span of 51 metres and provides cover for approximately 17,000 seated spectators on the East side of the ground. The front seating deck is supported directly on the ground while the middle and upper decks are of precast concrete supported on a steel frame structure. The plate opposite shows the stand under construction.

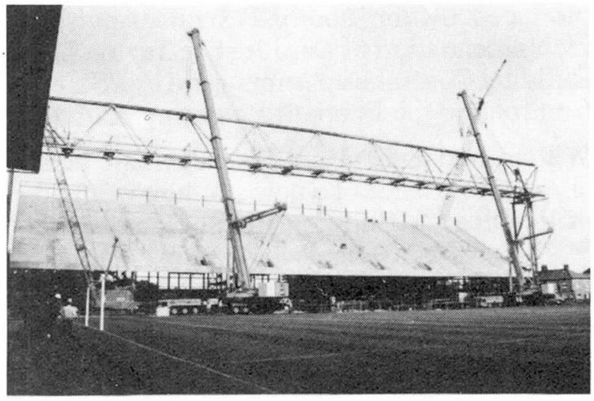


The Den Stadium : Lewisham : London

The first major British club to invest in a completely new stadium, post Hillsborough, has been Millwall Football Club. Their new 20,000 seated stadium incorporates many features which are designed to attract non–football events. Provision has therefore been made for increased levels of toilet provision, refreshment kiosks, hospitality suites etc. The seating decks are supported on a steel frame and the roof is of cantilever design. The roof spans vary from 23.5 metres to 25.5 metres. The plate opposite shows a view of the finished stadium from the rear of the South Stand.

Filbert Street Stadium : Leicester

Unlike most other clubs, Leicester City FC chose not to develop their secondary stands but to concentrate in the first instance on replacing their Main Stand. The new 9,000 seat Main Stand at Filbert Street incorporates a high level of facilities which not only have a match day role but also can be used for other non–sport purposes. The precast concrete seating decks at Filbert Street are supported on a steel frame, and the clear span roof takes its principal support from a 111.5 metres span "goal post" framework. Plate opposiite shows a view of the stand under construction.

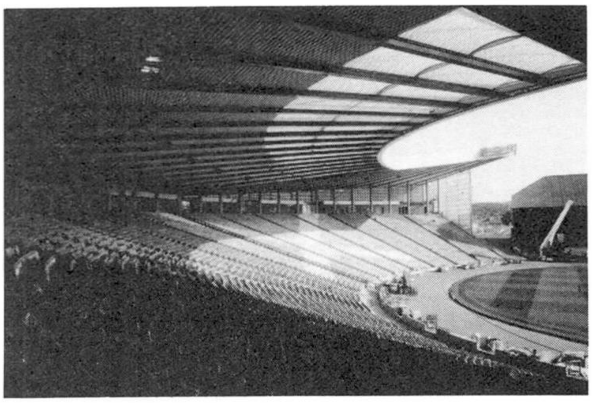


Murrayfield Stadium : Edinburgh

Murrayfield is the home of Scottish Rugby and hosts the Scotland Home International matches. Since 1992, it has undergone major redevelopment which, by September 1994, will see completion of a 67,500 all seated, bowl stadium. The roofs are all of cantilever design with a maximum clear span in the West Stand of 48.5 metres. The exposed roof trusses are fabricated from self weathering steel and have been left unpainted. The precast concrete seating decks are supported on a steel frame. Plate opposite shows Murrayfield in July 1993 with the East, North and South Stands complete and the West Stand under construction.

Hampden Park : Glasgow

Hampden Park is the traditional International ground for Scottish soccer. In 1937 its terraces accommodated its record crowd of over 149,000 spectators. Since then alterations have reduced the extent of the terraces and stands. Work on converting the terraces to seating commenced in 1993 and by 1996 a 60,000 capacity all seater stadium is programmed to be in place. The Hampden Redevelopment is relatively unique as it has retained the previous terrace profile, but has added roof cover and provided seating. The roof is of cantilever form with a maximum clear span of 42 metres. Plate opposite shows the East Stand nearing completion.



In terms of structural form there is relatively little which is consistent between the six stadia listed. Three, Elland Road; Murrayfield and Hampden Park are of bowl design, whilst Ibrox; Millwall and Leicester have four individual stands. Two, Ibrox and Leicester, have goal post roof support and four adopt the cantilever roof form. All with the exception of Elland Road have underslung cladding with trusses exposed above the roof. Leeds is overclad with trusses exposed beneath the decking. All six stadia have seating decks supported either directly on the underlying soil or on a precast concrete deck supported on structural steel. Only Hampden and Murrayfield incorporate translucency in the roof cover.

3. DESIGN CRITERIA

All stadia in Britain require to satisfy the requirements of the Building Regulations [10] which refer to British Standards Codes of Practice and to the "Guide to Safety at Sports Grounds" [3]. The latter document incorporates rules for design developedas a consequence of previous disasters, particularly those at Ibrox Stadium in 1979 and at Bradford in 1985. Other guidance is available principally that produced by the Football Stadia Advisory Council, a body set up, post Hillsborough, on the recommendation of Lord Justice Taylor. Design proposals are subject to audit by the Local Authority Building Control Department and by a Safety Committee representing Police, Fire Officers, Building Control and the Football Licensing Authority.

With formal audit procedures it would be reasonable to assume that the level of risk associated with poor performance of a new stadium would be very low. It must be appreciated, however, that Codes of Practice and Building Regulations were not written specifically for stadium construction and there are aspects of design which apply uniquely to large stadia construction. These particular design requirements may not be adequately covered by current design standards. Among the more significant considerations are:

- Dynamic Response of Roofs
- Dynamic Response of Seating Decks
- Progressive Collapse

3.1 Dynamic Response of Roofs

Design static wind loading on stadia roofs can be obtained from Codes of Practice and guidance notes or from the results of wind tunnel tests. Figure 1 shows the results of wind tunnel tests carried out on the East Stand at Murrayfield [5] and indicate that the values given in the British Code, CP3, Chapter 5 [4], were in this case conservative.

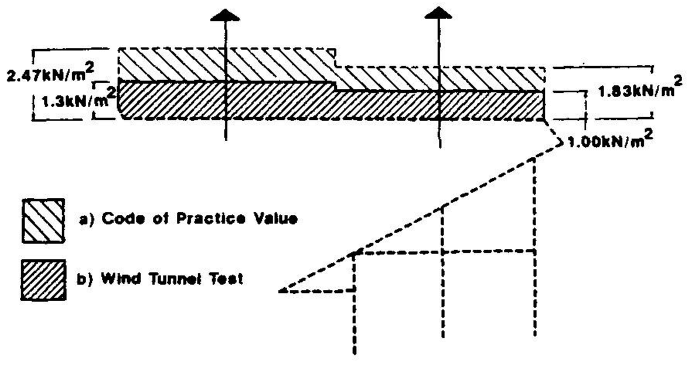


Fig 1 Murrayfield East Stand - Static Wind Pressures

With increasing spans, static loading is no longer the only consideration and natural frequency and wind excitation become of equal or greater significance. While there exists a great many references which can be used for static loads cases, very few equivalent sources of data are available to aid the designer to assess dynamic loading and associated structural response.

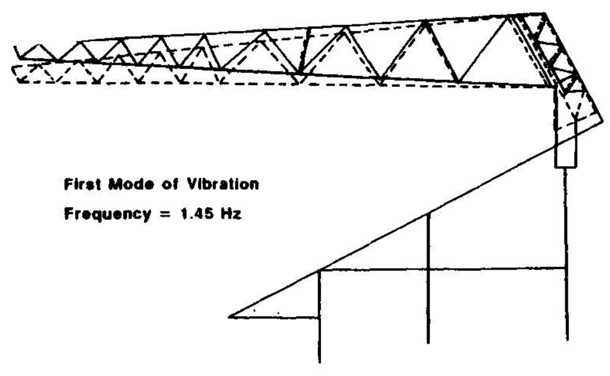


Fig 2 Murrayfield East Stand Structural Model

For the final phases at Murrayfield, with large cantilever roofs extending to 48.5 metres, it was decided by the designers that a rigorous check on dynamic performance was justified. The wind tunnel testing programme was therefore modified to produce a wind loading spectrum suitable for use as data for the Lucas software.

The results of the dynamic analyses for the 42.5 metre span North Stand indicated that the deflection range under the maximum dynamic case was 40 mm as compared to the static deflection range under wind loading of 350 mm. It was also noted, however, that dynamic behaviour was very sensitive to span of structure and to its stiffness. A paper describing in detail the dynamic analyses of the Murrayfield stands is in the course of preparation and will be completed after the opportunity has been gained to carry out dynamic performance tests on all the completed stadium roofs.

No reference is currently made in Codes of Practice to oblige designers to carry out dynamic analyses to verify the adequacy of their structural models. From experience, the author is of the opinion that rigorous analyses, including obtaining data from model tests is justifiable for all cantilever roof spans greater than 45 metres, or for roof trusses where the computed natural frequency approaches unity. It is also important that major roof structures are instrumented and monitored to create a reliable database of real performance from which analytical methods can be calibrated and informed design judgements can be made.

3.2 Dynamic Response of Seating Decks

Given that spectators in major stand structures are often influenced by music, chanting, rhythmical stamping and other similar co–ordinated activity where the crowd acts in unison, it is an omission that there is no mandatory requirement to address the question of dynamic performance of seating decks and their supporting structure. Although well documented problems have occurred, namely in a temporary stand at Corsica and in the Maracana stadium in Brazil [6], to date no criteria have been published or rules laid down to require designers to consider this important subject.

Published data would suggest that although small numbers of people indulging in aerobics can act in unison at frequencies up to 3 Hz, large crowds cannot co–ordinate their motion at frequencies greater than 2.5 Hz. This would imply that seating decks should be designed, therefore, on the assumption that they may be subjected in all directions to forcing frequencies of up to 2.5Hz.

Insufficient data currently exists for stadium designers to carry out accurate modelling of crowd activity and to correlate it with any degree of accuracy to the response of a particular stand structure. It is nevertheless of concern that no reference is made in Building Regulations, Codes of Practice or design guides for stadia in Britain that designers should compute the natural frequencies of the fully loaded spectator decks of their proposed structures and compare them with the potential frequencies of activity which might be generated by future occupants.

Further research and testing of completed structures under crowd loading is required to formulate a reliable design procedure and compliance parameters. Nevertheless minimum standards could be set from existing data. It is the author's view that until more definitive information becomes available seating decks should not have a natural frequency less than 3.5 Hz.

3.3 Progressive Collapse

Following the progressive collapse of a multi–storey block of flats at Ronan Point in London the British Building Regulations were revised to require that all structures in excess of 5 storeys high incorporate special provision to prevent disproportionate collapse consequent on the failure of a structural element.

In spite of the disastrous consequences which would ensue following the collapse of an occupied stand structure no special provision is made in British Building regulations to require that disproportionate collapse be considered as a design issue on stadia roofs or stadia deck structures.

It is the author's view that this is a serious omission from the Regulations and that all stadia structures should be designed to avoid disproportionate collapse following the failure of any one member. Such provision has been incorporated in the roof structures illustrated in Plates 3, 5 and 6 by designing the secondary roof trusses, which span between the main trusses, to carry the loading of a failed truss laterally to the primary trusses on either side. The primary trusses are also designed such that at ultimate capacity they can sustain the resulting additional loading.

In the case of the structure illustrated in Plate 4, the main "goal post" girder is designed with a double truss arrangement in the triangular form, shown in Fig 3. Should any one member of either truss fail the remaining structure is capable of sustaining the roof loading without collapse.

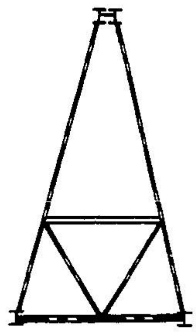


Fig 3 Leicester Main Stand Roof Girder Cross Section

The disastrous consequences of failure of a roof truss or seating deck are sufficient reasons for amending the Building Regulation to require a progressive collapse limitation on stadium design, but there are other special considerations which make such a requirement for stadium roofs even more pressing. Among the most important are:

- Stadium roofs are exposed, uninsulated and unheated and can, therefore, be exposed to micro–climates with high levels of condensation and thermal movements.
- Stadium roofs can be subject to very low temperatures, with the consequent increased risk of brittle fracture in steel components.
- Stadium roofs are subjected to dynamic excitation from wind loading leading to cyclic stressing and consequent increased potential for fatigue.
- Elements of stadium roofs can be inaccessible resulting in inspection and maintenance difficulties.

With regard to partial collapse following the failure of an element supporting the seating deck, the form of these elements is such that the rules contained in the Building Regulations for designing five storey buildings could readily be applied.

In addition to the requirement for specific clauses in the Building Regulations relating to stadia, there is the parallel need to focus the attention of Club Directors and Owners that they carry the primary responsibility for inspection, maintenance and repair of the complex structures which comprise their stadium. Currently the main focus of attention of most Club Directors is the performance of the team and the financial status of the Club. Too often stadium inspection and maintenance is relegated to an issue of minor importance where action need only be considered if Local Authority Safety Teams insist that maintenance work or additional safety measures are necessary.

CONCLUDING REMARKS

The six examples of post Hillsborough stadium developments illustrated testify to the progress being made to upgrade the spectator accommodation at major sporting venues in Britain. Standards have been set by the Building Regulations, Codes of Practice, The Guide to Safety at Sports Grounds, FSADC publications and guidance available from FIFA and other interested bodies.

In some fundamental areas the guidance available for designers is significantly deficient. In particular, research and guidance are required to address critical issues such as limiting design values for dynamic performance of both roofs and seating decks and to establish rules for limiting disproportionate collapse should a local structural failure occur.

Too often government input and finance into upgrading stadia design rules has been limited to an inquiry in the aftermath of a major disaster. Large stadia incorporate specialist structures and consideration of the issues discussed in this paper should not be neglected until the need to do so is proven by a disaster.

REFERENCES

1 REID WM., UK Football Stadia : Engineering for Crowd Safety Elsevier – 1993

2 The Building Regulations 1991. HMSO 1991 ISBN 0–11–015887–3.

3 Guide to Safety at Sports Grounds. HMSO 1990 ISBN 0–1–1–341001–8.

4 CP3 Chapter V : Loading. British Standards Institution.

5 REID WM., TRAVERS J., Wind Tunnel Testing of Sports Stadiums – Construction of Building Materials Vol 5 3 September 1991

6 BATISTA R., : Structural Dynamic Analysis of Maracana Stadium : Bench Mark : Sept 1993

Experience of Cupola Collapse with a Diameter of 237 m

Expérience tirée de l'effondrement d'une coupole de 237 m de diamètre

Erfahrung aus dem Einsturz einer 237-m-Kuppel

Jossif RASHA
Civil Engineer
Inst. of Steel Structures
St. Petersburg, Russia

Boris LUBAROV
Civil Engineer
Inst. of Steel Structures
St. Petersburg, Russia

Anatoly JOURAVLEV
Mechanical Engineer
Inst. of Steel Structures
St. Petersburg, Russia

Jury PLISHKIN
Civil Engineer
Inst. of Steel Structures
St. Petersburg, Russia

SUMMARY

The steel dome of 237 m in diameter collapsed in Russia in 1986. The construction of the dome and its finishing were completed. The load-carrying structure were made as two-layer latticed bar shell. Shortly before the collapse the outdoor air temperature changed from -20°C to +1°C during six hours. Due to the non-uniform heating some of the shell bars lost their stability and this caused the collapse.

RÉSUMÉ

En 1986, une coupole en acier de 237 m de diamètre s'écroula en Russie, après l'achèvement complet de sa mise en oeuvre. La structure porteuse se composait de deux coques formées de barres en treillis. Juste avant l'effondrement, la température de l'air ambiant s'éleva de -20°C à +1°C en six heures. La rupture de stabilité de certaines barres de treillis, par suite de leur échauffement non uniforme, provoqua l'écroulement de la coupole.

ZUSAMMENFASSUNG

In Russland stürzte 1986 eine Stahlkuppel mit 237 m Durchmesser ein, nachdem die Montage und Fertigstellung vollzogen waren. Das Tragwerk bestand aus einem zweischschaligen Raumfachwerk. Kurz vor dem Einsturz stieg die Aussenlufttemperatur innerhalb sechs Stunden von -20°C auf +1°C. Durch die ungleichförmige Erwärmung büssten einige der Fachwerkstäbe ihre Stabilität ein, worauf der Kollaps eintrat.

There was a competition announced in 1981 for designing of a long-span building 115 m high with a span of 250 m.
The building was meant for testing the equipment used for electric power lines at a voltage to 2000000V. It was suggested that the construction site should be located at a short distance from Moscow. Two designs were submitted for examination at the last stage of the competition.
Desigh No 1 elaborated by a team of Moscow civil engineers presented a building shaped as a flattened ellipsoid 237 m in eduator diameter. The building height was 119 m. See Fig.1.
The principal load-carrying structures were designed as a two-layer latticed shell at a spacing of 2.5 m between the upper and lower chords. The shell upper and lower chords were made of twin angles. The lattice between the chords was made of tubes welded to the angle flanges. A diaphragm 1,5 mm thick of weatherproof steel was welded to the upper members of the shell. The diafragm served as roofing and made the bars stable.
The heat-insulated boards of the suspended ceiling working as fire protection of the carrying structures at the same time were secured to the lower chords of the shell. The erection members were connected by high-strength bolts. The total weight of the steel structures was about 11000 tN.
Design No.2 was elaborated by a team of Leningrad (St.Petersburg) engineers. It was a structure 128 m in height made of a cylinder like part 80 m high and a hollow domelike roofing 227 m in dia with a boom of lift 47 m. See Fig.2. The cyliderlike framework was made of columns connected by cross-braces and the dome was designed as a circular ribbed structure. The total weight of the structures made about 11500 tN.
Both designs were supported by the necessary calculations of the structures made in accordance with the Russian Building Code (dead weight, snow load, wind load, thermal effect).
Design No.1 was chosen for construction mainly because of the architectural expressiveness of the building and the criteria unlikeness.
The main structures of the dome were erected by the middle of 1984. See Fig.3a. The erection and construction work completed in 1985. The overloaded members were checked for force increment at erection of technological equipment premises 600 tN in weight

at an elevation of +106.7 m. The test results gave good coincidence of the design model and the real work of the structures.

In 1986 the dome collapsed. Since it was early morning, there were no victims. Before the collapse took place, the construction site underwent very rare meteorological condition. The air temperature remained -20°C during 20 days. Then during 6 hours the temperature changed to +1 °C. Three hours after this the dome collapsed.

Let us analyse what changes happened in the stress conditions of the structures under such a sudden change of air temperature. The space 2.5 m high between the upper chord covered with cold steel sheets and the lower lagged chord turned to something like a thermos with a temperature of -20°C. The bars of the upper cold chord warmed up faster under the outside sharp heating than the bars of the lagged lower chord - see Fig.4. The difference in temperature of the chords according to the calculations could reach 15°C. Nonuniform heating of one chord to 1 °C gave the stress increment to 3 MPa in some of the bars and at 15°C this value made 45 MPa or almost 30% critical strength of the steel. Most probable the additional stresses brought mostly loaded bars to the loss of stability and caused the collapse.

The imperfectly thought-out solution of the enclosing structures resulted in the design diagram in the form of a latticed dome highly sensitive to the nonuniform temperature effect.

Conclusion.

1.When designing long-span structures it is necessary to use statistically treated meteorological data on the sharp changes of outdoor air temperature with determination of the temperature change speed and range and probability for 25, 50 and 100 years.

2.It is necessary to perform heat engineering and static calculations for the long-span structures for the stage of construction and operation in sharp condition of air temperature change in the building area.

3.When desighing the enclosing structures it is necessary to provide for equal temperature conditions of the load carrying structires.

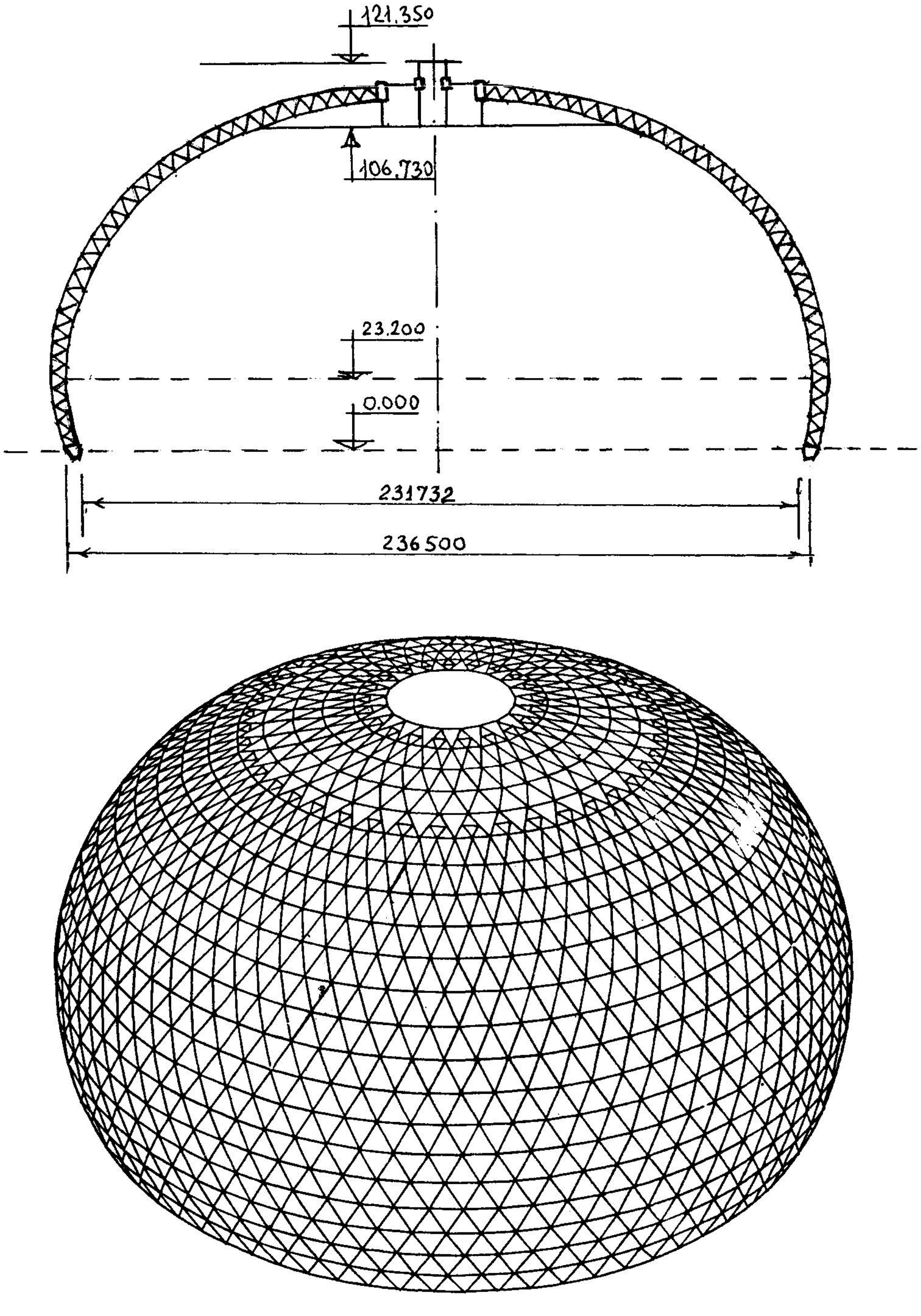


Fig. 1

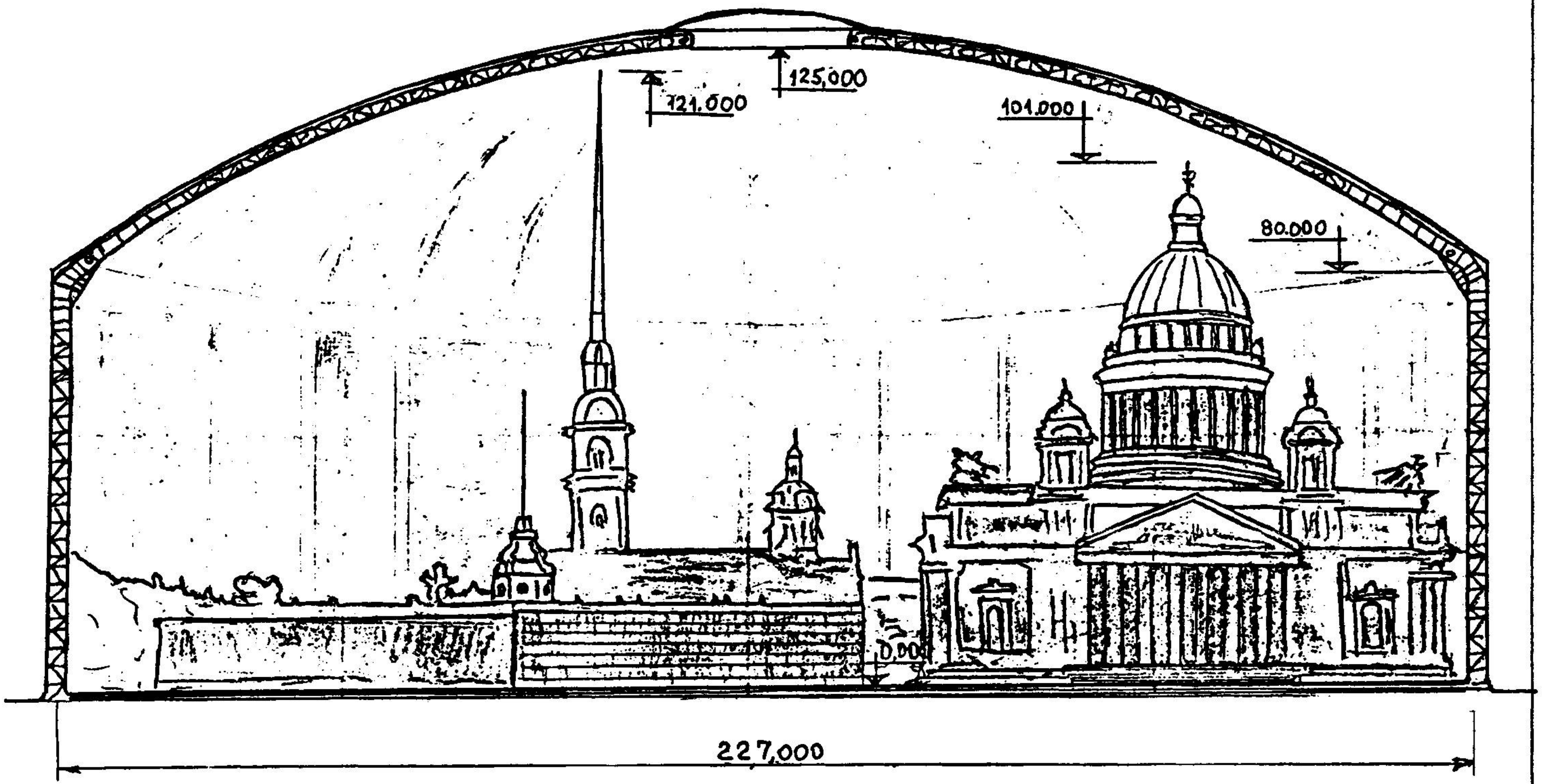


Fig 2.

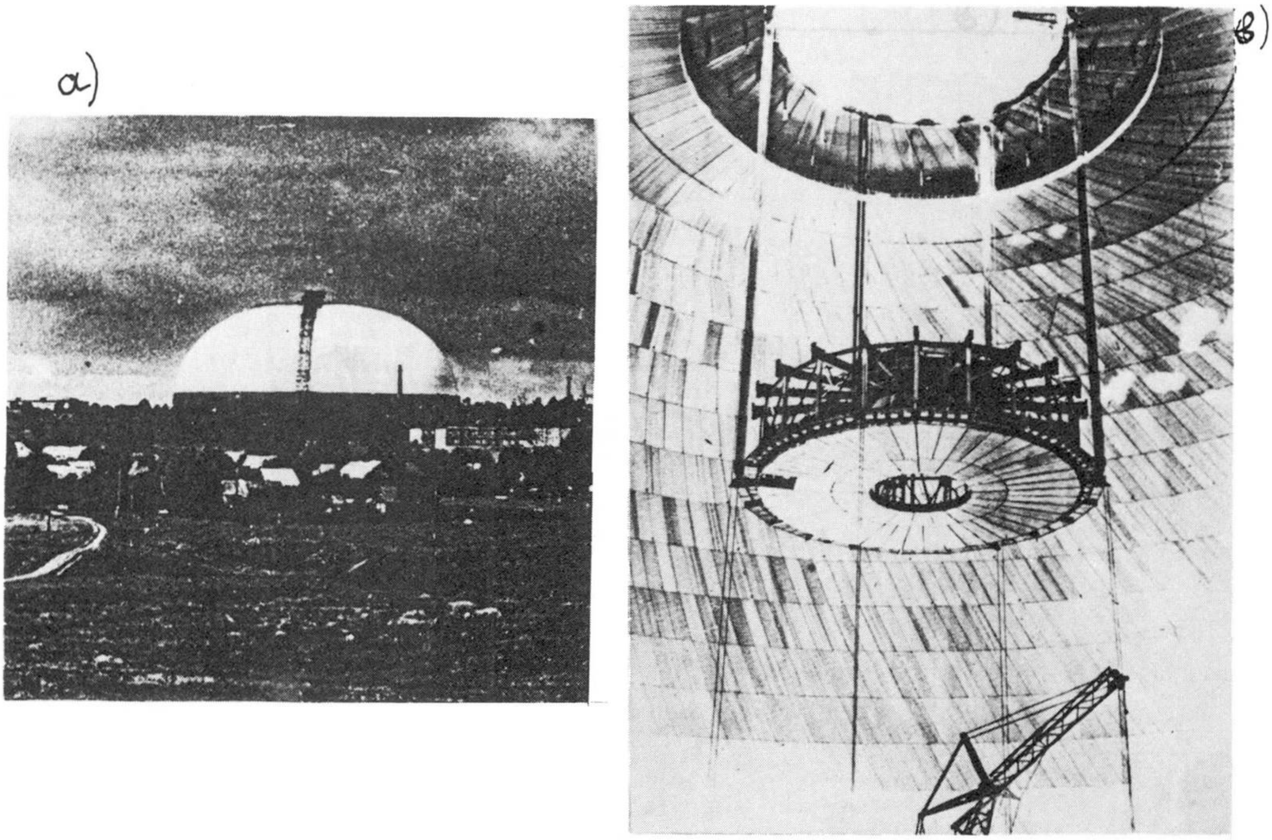

a)
в)

Fig. 3.

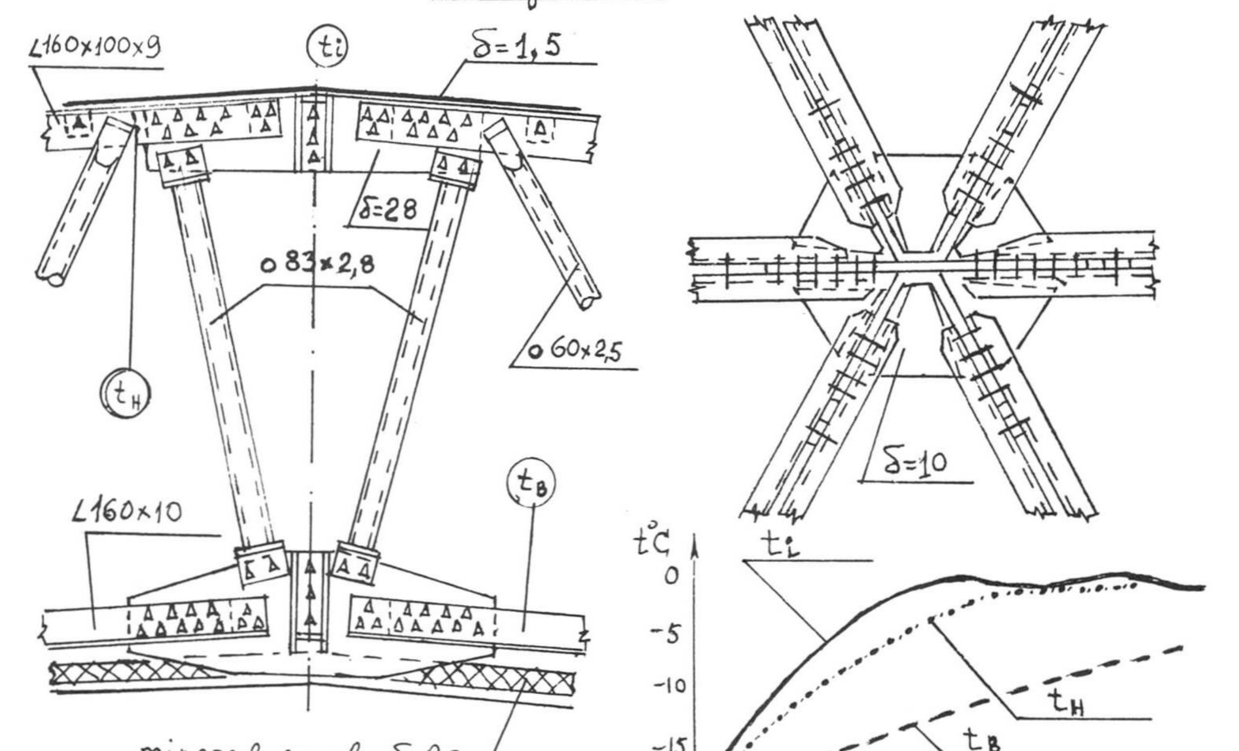

∠160×100×9
ti
δ=1,5
δ=28
o 83×2,8
o 60×2,5
tн
tв
∠160×10
mineral wool δ=80
δ=10
t°C
0
-5
-10
-15
-20
0 1 2 3 4 5 6 7 8 9 T
(hour)

Fig. 4.

Cathedral Structures and Fire

Les structures des cathédrales face aux incendies

Kathedralen und Feuer

Geoff CLIFTON
Director
Gifford and Partnres
Chester, UK

Geoff Clifton, born 1947 and now responsible for building engineering in several offices of Gifford and Partners. After wide experience of structural engineering his interest now concentrates on the engineering of historic structures and the interaction with archaeology. He is currently the Engineer to Wells Cathedral.

SUMMARY

The paper considers the historical perspective of the construction of Cathedrals in the context of previous public assembly buildings. It examines the history of fires in Cathedrals and the reason for their occurrence. The methods of providing structural fire protection are discussed relative to the fire prevention and protection plans. The methods of fighting fires is considered with some of the consequences. Finally an overview is made of the current enthusiasm on fire compartmentation.

RÉSUMÉ

Cet article fait l'historique de la construction des cathédrales dans la perspective des bâtiments destinés aux rassemblements publics. Il passe en revue les incendies ayant endommagé diverses cathédrales et en étudie l'origine et les causes. En se référant aux méthodes de prévention et de protection contre l'incendie, il expose les mesures structurales de protection à envisager, les procédés de lutte contre le feu et quelques conséquences possibles. L'auteur souligne l'engouement actuel pour le compartimentage destiné à freiner l'extension de l'incendie.

ZUSAMMENFASSUNG

Im Kontext zuvor diskutierter öffentlicher Versammlungsstätten wird die Bauweise von Kathedralen historisch beleuchtet. Dabei kommen die geschichtlichen Feuersbrünsten in Kathedralen und ihre Ursachen zur Sprache. Mit Bezug auf Brandverhütung und Brandschutz werden mögliche konstruktive Massnahmen, die Art der Feuerbekämpfung und ihre Folgen diskutiert. Abschliessend wird auf den gegenwärtig vorherrschenden Enthusiasmus für Brandabschnitte eingegangen.

1. HISTORICAL CONTEXT

1.1 Our great Norman Cathedrals and Minsters that survive in a number of our City's were an extraordinary achievement. It is interesting to look at their precursors. The Saxon Cathedrals, many of which were on the same site are an obvious choice, but I believe that their real origin lay in the construction of the Roman Bath Houses and Basilicas, which were built in many places throughout England and were of a surprisingly similar size and style to our Cathedrals.

1.2 The Basilica (public hall) in London was 150 m long with a nave and side aisles, the nave being 17 m wide and 25 m high, this approximates to the size of the main nave and choir of St. Pauls Cathedral. The Principia (Headquarters building for the army) in Caerleon whilst only 64 m long was of cruciform shape with a 25 m wide nave and a height probably of around 30 m. Bath houses were also built in similar sizes. Whilst Basilicas often had timber roofs, in Bath Houses barrel vaults in tiles were sometimes used, as in the City of Bath. It is interesting that the records show that in England the Temples were generally smaller than the Basilicas and Bath Houses. Leisure centres were obviously more popular than churches even in 200 A.D.!

1.3 However to return to our great Cathedrals. Once the Cathedrals had been completed, and some collapsed during construction as Master Masons and Bishops strove to stretch the boundaries of existing rules, the buildings then survived well providing that they were well maintained and politically supported. The biggest threat to their existence being fire or alterations affecting their overall stability. The additions of spires to pre-existing towers was a common cause of failure, though this often took many decades to occur. Salisbury Cathedrals splendid medieval spire being the only real survivor. However we are concerned here primarily with fire and as an introduction it is worth looking at the history of two of our Cathedrals.

2. CAUSES OF FIRES

2.1 York Minster is an obvious choice given the publicity from the 1984 fire. Ten major fires are recorded in the history of the buildings on this site. The first three occurred in the Saxon Buildings pre-dating the present Minster and these recorded fires were major sackings of the buildings by marauding Vikings and finally by William the Conqueror as a punishment for the City resisting his troops. Thereafter the current Norman Minster was constructed. The first recorded fire being an accidental fire in 1137, though there is no information on its cause. Similarly in 1464 there is a record of a well within the Church being used for fire fighting, but with little more information. In 1745 there was a lightning strike that threw down a pinnacle but fortunately caused no fire. In 1753, whilst re-leading the roof, the workmen left a dish of hot coals on a gutter which ignited the timber resulting in a fire in the roof over an aisle. In 1829 there was a major fire in which the roof, the organ and all the internal timberwork to the Choir was lost and this was an act of arson by a lunatic. In 1840 there was a fire in the tower as a result of a candle being left in the Bell Chamber. Finally in 1984 there occurred the major fire in the South Transept in which the roof was completely lost. The cause of the fire has not been proved, but is believed to have resulted from a lightning strike, when a flash over from lightning tape to an electrical fitting set light to roof timbers.

2.2 The present building therefore has a record of six major recorded fires over a period of 850 years. However it is known that in the last couple of Centuries there have been a number of minor fires occurring within the building, that had been quickly put out and caused little damage.

2.3 Wells Cathedral has a more fortunate record, in that during its history it has only suffered one significant fire when the spire caught fire and fell in 1439. No evidence remains as to the cause of the fire. Otherwise the Cathedral has been fortunate with no other reported fires.

2.4 The history of the York Minster in a good example of the threats and causes of fire with historically five major causes being apparent:- Lightning, Hotwork on the Roof, Candles, Arson and Accident.

2.5 If we consider the current threats to buildings, candles have largely been replaced by electricity. However it is a moot point as to whether this has reduced or increased the threat, as figures appear to show that 50% of fires in Listed Buildings are caused by electrical faults of one sort or another. The three most common electrical causes being old wiring, adhoc extensions and heat sources of one type or another.

2.6 Lightning is still a concern and even with modern lightning protection systems secondary affects can be disastrous as was probable in 1984 fire at York. The dangers of contractors hotwork is now I well understood, and the relatively recent fire at Uppark House highlights these dangers. Most institutional owners of historic buildings have formal and well regulated systems for hotwork, which are essential to reduce the risk to acceptable levels. Arson is a continual concern and it is estimated that nationally 25% of all fires are deliberate and that these are responsible for over 50% of the total national loss due to fires. The final cause is an ever present concern, the accidental fire due to carelessness in smoking, cooking, work rooms etc. The fire at Windsor Castle seems likely to have been caused by a tungsten spotlight being placed too close to curtains screening the alter in the Private Chapel.

3. FIRE PREVENTION

3.1 It is now common practice for Cathedrals to have fire plans covering the prevention, protection from, and detection of fires and also to have a detailed action plan covering what to do in the event of a fire. Clearly prevention is the most important of these issues and the most important element in prevention is people. The maintenance of vigilance and adherence to good working practices being the best preventative measure of all to avoid the risk of fires.

3.2 The vigilance of all the building users being the greatest protection against arson and accidental fires. The adherence to good working practices including the correct use of hot work permits, the correct installation, inspection and maintenance of all electrical and lightning circuits, and the appropriate working procedures for heating installations and other equipment.

4. FIRE PROTECTION

4.1 The protection of the building against fire falls into two elements, the passive protection, such as structural measures to limit the spread of and to contain fires and active measures to fight the fire. Passive protection of the structure includes compartmentation and venting, and the protection of structural materials to give them enhanced fire resistance. Cathedrals by their very nature are large open buildings with a relatively light fire load at floor level, though many Choirs have a significant amount of timber and organ lofts are a well known hazard. The main structure is normally of stone and the greatest fire load is therefore usually in the timber roof. Compartmentation is an important element for the containment of fire spread and at ground level compartmentation is negligible with one large open space. Many of the Cathedrals have stone vaulted ceilings and these provide a splendid fire compartment between the body of the building and the roof spaces with the highest fire load. Also most Cathedrals have central towers and these usually form a competent fire-break between the main four roof spaces over the Nave, Transepts and Choir providing that accesses through the walls have fire doors where appropriate. The fire at York was stopped at the Tower but in order to prevent the fire spreading under the crossing, the transept roof close to the Tower had to be deliberately collapsed by the fire brigade.

4.2 There is much discussion at present about the need to further compartment the roof spaces in our Cathedrals by the introduction of vertical fire compartments, at say 25 metre intervals through these spaces in an effort to prevent the spread of fire should one occur. Apart from the major roof spaces the fire at Windsor Castle highlighted the danger of hidden voids in buildings, which can spread a fire very rapidly as the voids may act as chimneys.

4.3 The spread of fire can also be partially contained by venting to atmosphere near the source, so preventing the rush of hot gases and smoke to elsewhere in the building. The venting the roof spaces can be achieved with vents on fusible links, so that in the event of a fire roof vents are opened, allowing the fire to burn upwards and to inhibit its spread.

4.4 The predominate structural materials used in Cathedrals are stone and timber. Stone has a good fire resistance and whilst it is possible to treat timbers to reduce the surface spread of flame and also to impregnate them with retarders, to my knowledge no-one has yet proposed such a solution for the existing roof timbers in one of our Cathedrals. The cost of the treatment being excessive for the reduction in risk that would be achieved.

5. FIRE DETECTION

5.1 Detection is the next item of the sequence preceding the implementation of active protection systems. Early detection of a fire is crucial and as can be seen from the history of York Minster there have been a number of fires in the last two Centuries which were minor, quickly detected and quickly put out, but for example the fire in 1829 which destroyed the Choir was lit at between 2 and 3 o'clock in the morning and was not discovered until 7 a.m., by which time it had gained such a hold that it took the best part of a day to put out. It is common place now to have smoke detectors throughout Cathedrals connected to remote alarm facilities.

5.2 There is however a dichotomy here, in that if you have a roof space with no lighting and no detectors there is no need for any electrical wiring in the area. The installation of detectors requires the installation of wiring and it is an interesting discussion as to whether the increased risk of fire by the installation of wiring is offset by the reduction in risk by early detection. The gains of early detection certainly do outweigh the added risk of electrical circuits, providing that the circuits are properly installed and well maintained. However if you consider the case of Wells with one fire only in its nine hundred year history and this was probably due to a lightning strike on the spire which no longer exists, it could be argued that we have increased the risk of a fire by the introduction of electrics for detectors and lighting in the roof space. It is possible to use detectors with radio links so obviating the problems with wiring, but they can suffer from operational interference.

6. FIRE FIGHTING

6.1 In the event of a fire being detected there are various active fire fighting systems that can be used, which are in common usage in modern buildings, where they have an exceedingly good record. The Loss Prevention Council records show that, where installed, sprinklers suppress 98% of fires before they take hold. They have been considered in Cathedral roof spaces but the dangers of inadvertent use, the intervention that they cause to the existing historic structure and the costs have made them so far inappropriate. A similar conclusion being drawn for the Royal Palaces in Sir Alan Bailey's Report. Mistprays are a relatively new technology that combined with early detection, can be effective and overcome many of the concerns about damage to fabric from inadvertent use. But as for sprinklers the combination of disadvantages make them unlikely to be used. Another active automatic system would be inert gases, but the spaces in Cathedrals are so large and so draughty that they would be totally ineffective. Other in-built systems that have been considered in Cathedrals include the installation of blown foam equipment in the roof voids, but simple tests have not as yet proved their effectiveness in generating sufficient foam at the right location.

6.2 The only positive assistance of which I am aware is that used on many Cathedrals is the installation of dry risers up to the roof spaces, so that the Fire Brigade can connect hoses at this level to fight a fire.

6.3 To consider further some of the aspects of fighting the fire and its consequences. Safe access for the Fire Brigade is of prime consideration for the Officer in Charge of fighting the fire and many Cathedral roofs, particularly those with timber vaults, would be too dangerous for fire fighters to enter in a fire and access along the parapets would similarly be too hazardous, so that the fire would probably have to be fought from outside hoists and ladders. Cathedrals with stone vaulted roofs create a safer working platform for the fireman though these roof spaces are invariably cluttered with many ties, cross-beams, raking members etc. so that access is not easy.

6.4 One of the consequences of fighting a fire is the huge volumes of water that are usually pumped into the building which creates significant problems of its own. A typical vault pocket might contain 20 tonnes of water which would almost certainly cause collapse of the vault fields and in a Cathedral with particularly slender walls, the out-of-balance loading prior to collapse of the vault fields could result in instability of the walls. The large volumes of water will saturate the stonework and the rubble fill present in many walls and the thousands of gallons of water percolating into the foundation material could in some soils cause short and long term foundation movement. It is not just the fire that creates structural problems but the consequences of the necessary fire fighting techniques which can be equally damaging.

6.5 The need to consider all these issues in a combined and balanced manner is crucial and must be addressed as a policy matter. A fire plan can be drawn up covering not only these issues but the evacuation of people and items of value, as well as the disaster plan for coping with the aftermath.

7. CONCLUSIONS

7.1 Having quickly covered some of the aspects of fires in Cathedrals I would like to make a few general observations. The Country has suffered a number of significant fires in historic buildings over the last few years including Hampton Court, Uppark House, York Minster, Windsor Castle and this unusual concentration of major fires in our heritage buildings has I believe, caused something of an overreaction to the problems of fire in historic buildings. The addition of compartmentation within the major roof voids of our Cathedrals is an issue which is being accepted but which I feel may be counter-productive. The compartments can only be of half an hour to one hour rating and being retrofitted within a complex building fabric will have difficulty achieving significant containment. What is highly likely is that the installation of these compartments will create further enclosed spaces within the roof void where air cannot easily circulate and are very likely to increase the problems of corrosion of lead and decay of timbers. The inclusion of a fire compartment as a possible measure to inhibit a possible fire, may therefore be causing the very probable deterioration to materials which may have been in the roof for nine hundred years. Also the inclusion of these compartments within the roof spaces, destroys the appearances of these splendid roof voids, many of which put our best medieval barns to shame. Each building must be considered separately on its merits.

7.2 I believe there should be more active discussion of the view that we should perhaps accept that there will be a major fire periodically in our historic buildings, but that a major loss and replacement is better than disfiguring most of the heritage structures in the Nation. Many of these buildings have been with us for nine hundred years, let us not over-react in the space of a few years and take actions that future generations will regret.

References:-

- Heritage Under Fire: - Fire Protection Association.
- The Fires of York Minster: - Pitkin Pictorials Ltd.
- Wells Cathedral: - A History - Edited by L S COLCHESTER.
- Fire Protection Measures for the Royal Palaces - SIR ALAN BAILEY et al.

Fire Safety Engineering of Assembly Buildings

Étude de la protection contre l'incendie pour des lieux de réunion

Brandschutzprojektierung für Versammlungsbauten

Gordon COOKE
Civil Engineer
Fire Research Station
Borehamwood, UK

Gordon Cooke graduated in mech. engineering at Cardiff Univ. in 1960. He worked on the use of steel in industrialised housing before joining a London firm of Consulting Engineers where he became a Partner. He joined Fire Research Station in 1975, obtained a PhD in fire engineering and currently works on harmonisation of European fire matters and fire safety engineering.

SUMMARY

Assembly buildings are becoming larger and are often used for several disparate activities. Existing codes of practice for fire safety in buildings may not have caught up with leading-edge developments. Design from first principles using fire safety engineering methods is then necessary and it is the purpose of this paper to describe a proposed UK method and illustrate its application to a hypothetical assembly building.

RÉSUMÉ

Les lieux de rassemblement deviennent toujours plus grands et sont utilisés pour des buts fort dissemblables. Les normes existantes de protection contre l'incendie n'ont probablement pas toujours suivi les plus récents développements, il est donc indispensable que les considérations techniques se réfèrent aux principes élémentaires de la protection contre le feu. L'article présente une proposition britannique relative à cette protection à l'aide de l'exemple d'une salle de réunion hypothétique.

ZUSAMMENFASSUNG

Versammlungsbauten werden immer grösser und für mehrere ungleichartige Zwecke geplant. Die bestehenden Brandschutznormen haben vielleicht nicht mit den allerneuesten Entwicklungen Schritt gehalten. In solchen Fällen ist eine ingenieurmässige Betrachtung ausgehend von Grundprinzipien des Brandschutzes notwendig. Der Beitrag erläutert einen britischen Vorschlag zur Methodik am Beispiel eines hypothetischen Versammlungsbaus.

INTRODUCTION

Over the past two decades there has been a welcome move in the United Kingdom from comprehensive prescriptive building regulations to brief functional regulations supported by non-mandatory detailed technical guidance. This combination of regulations and guidance has served the country well - the UK has a good record for safety of life in fires in buildings. It is however accepted that buildings are becoming more complex and larger, placing more people at risk from fire than before: This is particularly true of large public assembly buildings.

Present technical guidance (such as the Approved Document B which applies to new buildings and alterations to existing buildings in England and Wales, and the supporting series of BS 5588 Fire Precautions in Buildings codes) does not, except in a few instances, provide a basis for calculations of fire safety to be made based explicitly on engineering principles. It is, for instance, very difficult to assess the effect on life safety of changing active or passive fire precautions since the basic principles and calculation methods for trade-off have not been written down.

A methodology based on sound engineering principles and employing calculation tools is needed to facilitate the design of those buildings for which existing technical guidance is inappropriate. This methodology is called fire safety engineering.

There is at present no internationally agreed definition of fire safety engineering. Here it is assumed to have the following widest meaning.

> 'The application of engineering principles, rules and judgement based on a scientific appreciation of the phenomenon of fire and its effects to:
>
> - save life, protect property and preserve the environment
> - quantify the hazards and risk of fire and its effects and
> - evaluate analytically the optimum protective and preventative measures necessary to limit within prescribed levels the consequences of fire.

Fire safety engineering has many benefits. It can:

- facilitate different ways of designing buildings having comparable safety levels
- facilitate more economic design of complex buildings while retaining safety levels
- overcome the restraints on design imposed by prescriptive regulations/codes
- identify topics of fire research which have a major bearing on life safety
- enable drafters of regulations and codes to improve the consistency of information, and justify the removal of out-dated traditional measures.

It was clear that a Fire Safety Engineering (FSE) methodology was needed which took account of many factors including: characteristics of the building including fire safety installations; characteristics of the occupants; intervention by the fire brigade; environmental conditions; and fire safety management.

Time-based calculation methods would be needed for determining:

- rate of heat release
- smoke production, toxicity and smoke spread
- fire severity and fire spread
- locations of occupants during evacuation

In 1989 a format and list of contents for a comprehensive Code of Practice on the application of fire engineering principles to fire safety of buildings was placed before the British Standards Institution (BSI). It was intended that the proposed code would cover general principles, life safety considerations, property safety considerations, mitigation of socially unacceptable events, and reduction in economic loss. Towards the end of 1990 a small group of fire safety engineers (which included the author) was formed to undertake a 3 year contract, administered by BSI and funded by the Department of Trade and Industry (DTI), of narrower scope which would culminate in a Code of Practice giving a framework, a methodology and a set of principles for the fire safety engineering design of new and existing buildings. A draft of the code was submitted to BSI in January 1994 for discussion. It guides on deterministic and probabilistic methods[1].

The basic procedure is to make a qualitative design review followed by a systems analysis. The qualitative design review (QDR) is needed because the interaction of fire, building and occupants gives rise to a large number of possible fire scenarios bearing in mind that fire can occur in any room in a building and can travel along many different routes. The review requires that the building designer (eg architect) explains to the fire safety engineer the concept and details of building usage, activities within rooms, location of circulation spaces in normal use, and the emergency evacuation strategy, if any. As part of this review it may become clear to the experienced fire safety engineer that there are several fire hazards which give rise to life-threatening conditions which require in-depth consideration if they cannot be removed by, for instance, the addition of a fire barrier or an automatic fire suppression system. The engineer can then focus his attention on the areas of the building likely to affect the life threat scenario(s) identified.

The objective of the QDR is to review the architectural design, identify potential fire hazards and define the problem in qualitative terms suitable for detailed analysis and quantification. Another important function of the QDR is to establish one or more fire protection schemes (trial designs) that are considered likely to satisfy the fire safety objectives. On major projects the QDR should be carried out by a group that includes members of the design team and one or more fire safety engineers. It is recognised that tools for computation and data for quantification will not always be available and the application of engineering judgement within the QDR will then be important.

The next stage is to make the detailed analysis. The draft code uses a sub-systems (SS) approach which is illustrated in Figure 1. Six sub-systems can be used ranging from SS1 'Initiation and development of fire' to SS6 'Evacuation'. Output data from one sub-system are the input data for other sub-systems and this is shown in the Figure. Before the sub-systems can be used data must be compiled which characterises the occupants, the fire safety systems and those parts of the building which influence the fire scenarios identified in the QDR.

Not all six sub-systems necessarily have to be used in a fire safety engineering assessment. For example if the objective is only to establish that occupants will not be overcome by smoke, SS1 is used to provide the rate of heat release data. SS2 takes these data and, using air entrainment factors, calculates at appropriate time intervals which areas of the room or building are contaminated by smoke. The locations of occupants in the building at different time intervals is calculated in SS6 and the outputs of SS2 and SS6 are compared to see if any occupants are in areas contaminated by smoke. If they are, the design is altered and, if appropriate, the sub-systems analysis is repeated. Further information on the draft BSI Code of Practice is available[2,3].

HYPOTHETICAL EXAMPLE OF FSE METHOD

A large diameter shallow light-weight dome is to be built in an urban area for holding temporary exhibitions, pop concerts, boxing tournaments and other sporting events. Simplified cross-sections are shown in Figure 2. The author emphasises that the design is purely hypothetical and has been conceived solely to provide a basis for this study.

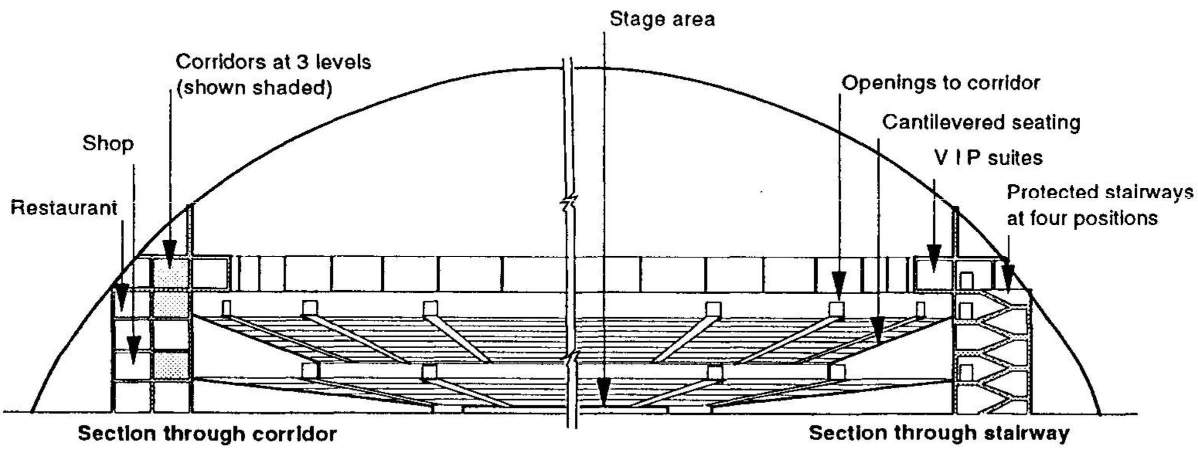


Figure 2. Typical sections through assembly building

A fire safety engineer (hereafter called the engineer) is appointed late in the design stage when the building control officer discovers that roof vents are not to be provided and he wishes to obtain an independent expert view to be sure that evacuation can be completed before the building becomes smoke logged. The engineer's brief becomes wider and involves making an assessment of the fire safety features in all of the building. The fire safety engineering study begins. First the objectives are agreed: safety of occupants and professional firefighters is of paramount importance; the developer is not concerned about property damage; and damage to the environment by contaminated fire fighting water is unlikely to be a problem.

The qualitative design review is commenced. The engineer obtains from the building designer a 3-dimensional visualisation of the building and a knowledge of how the building is intended to work in normal use and when fire occurs. This is the point when characterisation of the building and occupants is required and the following data are collected.

The framework is unprotected steel with floors of composite steel/concrete construction. The roof comprises a tubular steel geodetic space frame clad with sandwich panels having facings of sheet steel and a core of rigid polyurethane foam for energy conservation. Four large capacity stairways are provided for normal entry and egress and these are intended to be used for escape if fire occurs. Firefighting facilities are confined to hydrants outside the building and hose reels and portable fire extinguishers within. The building is not sprinklered and there are no roof vents. Audience seating is of upholstered moulded plastics which is supported by ramped unprotected steel framing. The upper framework for the seating is cantilevered. The flooring immediately underneath the seating is also composite steel/concrete. At the top of the audience seating there is a wall which extends from ground level to roof level with openings at sixteen positions around the circumference where people can move from the seating into the outer part of the building. There are sixteen equi-spaced aisles oriented radially, and three and six circumferential aisles in the upper and lower seating areas respectively. Above the audience seating there are some VIP suites which are fully glazed along their fronts. Conditioned air is blown from above the VIP suites downwards and towards the centre of the building. There are three circumferential corridors giving access to and from the audience seating and the VIP suites, one at each level. These corridors connect with the four staircases but with no intervening fire doors. The corridors serving the two ramped seating areas also contain a number of units such as snack bars, licensed bars, small shops, restaurants and toilets.

The QDR is continued. The engineer undertakes a fire hazard analysis to locate areas in the building where a life threatening fire might occur. First he identifies the worst fire that might arise if it occurred in the centre of the building. Using the methodology in SS1 he determines that the highest fire load density is associated with exhibition usage and it is assumed that initially fire is confined to an exhibition stand nominally 3.5 m square which, using plausibly pessimistic data, corresponds to a 20 MW fire.

The engineer agrees with the building control and fire authority that the smoke can be allowed to descend to the level of the top of the VIP suites, Figure 3(a), with safety if evacuation of all occupants into the protected corridors is complete by that time.

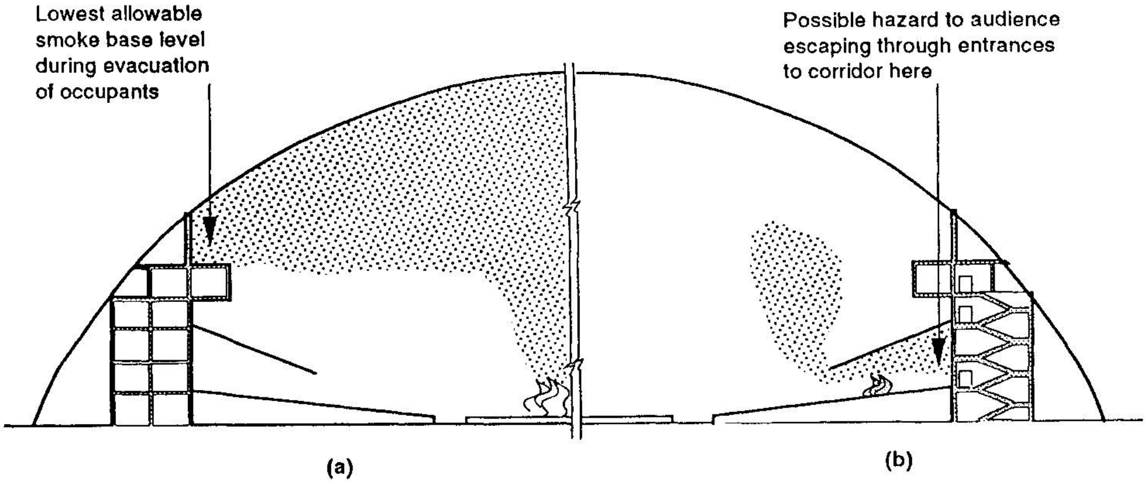


Figure 3. Possible life-threat scenarios

SS2 is now used. The smoke fill time is calculated using an appropriate model (eg the axi-symmetric plume mass flow model given in the BRE micro-computer package ASKFRS). The model assumes that the smoke is contained within a rectangular volume and this means that the volume of the dome above the top of the VIP suites - the smoke reservoir in this case - has to be represented by a rectangular shape of the same volume. The input to the model is the length, width, height and depth of the smoke reservoir, and the smoke layer temperature which corresponds to the 20 MW heat release rate. The output is, say, a 10 minute smoke fill time. This is compared with the evacuation time of, say, 7 minutes derived from sub-system 6 or derived independently by the architect. The 3 minute safety factor is agreed by all to be adequate since the smoke fill calculation assumes that the fire is producing a constant 20 MW whereas detection of the fire and commencement of evacuation would have occurred in the preceeding fire growth period. Thus the 20 MW design fire is a worst case scenario.

The fire authority reminds the design team that it has a responsibility to provide a search and rescue service in addition to fire-fighting and wishes to know the fire conditions on arrival at the site. The engineer agrees with the fire authority the likely time taken from fire detection to time to gain access within the building. The parameters listed in SS5 are relevant here. The smoke level at the agreed time is calculated and found to be acceptable to the fire authority. During this debate the method of fire detection is reviewed and it is agreed that flame detection should be explored because of possible delay in smoke detection caused by deflection of the smoke plume by the conditioned air blown from above the VIP suites.

The engineer and the fire authority raise the problem of smoke clearance after a fire and the client agrees to install a small number of vents at the centre of the roof.

As part of the QDR the engineer notices that fire in the lower-level audience seating could cause the nearest exit doorways to be blocked by smoke, Figure 3(b). The likelihood of this happening depends on the ignitability, rate of heat release and smoke production of the upholstered plastics tip-up seats. He suggests two alternatives. One is to determine the rate of heat release of one or two burning seats in a test using a full size furniture calorimeter prior to a smoke fill calculation. The other is to increase the time for evacuation by improving the resistance to fire of the seating: the engineer proposes using a higher performance standard such that the seats satisfy the criteria for ignition source 0 (which represents a smouldering cigarette) in BS 5852: Part 1: 1979 and ignition source 5 (which represents some burning newspapers) in BS 5852: Part 2: 1982. The costs for the second option are found to be acceptable.

A further scenario is presented by a large shop with a fully glazed front which opens onto one of the protected circumferential corridors, Figure 2. The hazard is a fire in the shop which becomes well developed so that, when the glazing fails, a considerable volume of hot smoke will suddenly flow into the corridor presenting a hazard to people there. From SS1 it can be deduced that the rate of heat release of a fire in a shop can be represented by a fast 't-squared' fire. These data can be used as an input to the appropriate equation (the equation for smoke flow from an opening) in SS2 which takes account of the air entrained in the plume as it emerges from the shop and rotates through 90°. Having entered the corridor the smoke loses heat to the surroundings, becomes less bouyant and increases in depth the further it travels. The length of the circumferential corridor is large and it is therefore essential to allow for heat loss from the smoke using information on the thermal properties of the enclosing surfaces. It may be necessary to create smoke reservoirs within the corridor using smoke screens to retain buoyancy. However, the engineer suggests that the problem can be circumvented (and the need for the smoke fill calculation thereby avoided) by the use of a vertical-drop shutter on the shop front. The shutter is designed so that it descends to a height of 2 metres above floor level on actuation from a smoke detector, and only closes fully when the temperature of the fusible link used to actuate the shutter exceeds the life tenability temperature of, say, 120°C. Such a shutter enables people from within the shop to escape with safety and yet provide a barrier to massive invasion of the corridor with smoke.

The engineer may identify a number of other features which need improvement such as the provision of appropriate levels of fire resistance in those rooms used to store materials. Recommendations given within parts of the BS 5588 codes on fire precautions in buildings are also applicable to a number of matters.

At the end of the study a report is prepared which contains information given under the headings in the Appendix.

CONCLUSIONS

This paper has described the approach followed in the development of the draft British Standard Code of Practice on fire safety engineering. A hypothetical assembly building has been used to show a few of the ways in which the code can be applied to an assembly building.

REFERENCES

1. Code Drafting Panel. Draft British Standard Code of Practice on the application of fire safety engineering principles to fire safety in buildings, January 1994. Presented to BSI in January 1994 but not yet (mid-January) openly available.

2. COOKE G M E. The philosophy of fire engineering being developed by the British Standards Code Drafting Panel, CIB/W14 Symposium: 'Engineering Fire Safety in the Process of Building Design', held in the University of Ulster, Northern Ireland on 13-16 September 1993.

3. DEAKIN A G and COOKE G M E. Future codes for fire safety design, IFS/FRS Technical Conference 'Fire safety by design: a framework for the future' held at the Fire Research Station, Borehamwood on 10 November 1993. To be published in Fire Safety Journal.

APPENDIX. THE CONTENTS OF THE FSE REPORT

The format of a report will depend on the nature and scope of the fire engineering study but it should typically contain the following information.

- objectives and scope of the study;
- description of the building and its fire safety installations
- description and characteristics of the occupants
- results of the qualitative design review (QDR) including: membership of the QDR team; fire safety objectives; results of the hazard analysis; basis for selecting fire scenarios for analysis; acceptance criteria; trial designs; and influence of fire-safety management;
- results of the systems analysis including: description of models used and relevant limitations; the input and output data for each sub-system; and the analysis of data including information on uncertainty of input data and calculated data.
- comparison of sub-systems output and tenability criteria
- conclusions
- references
- appendices for details

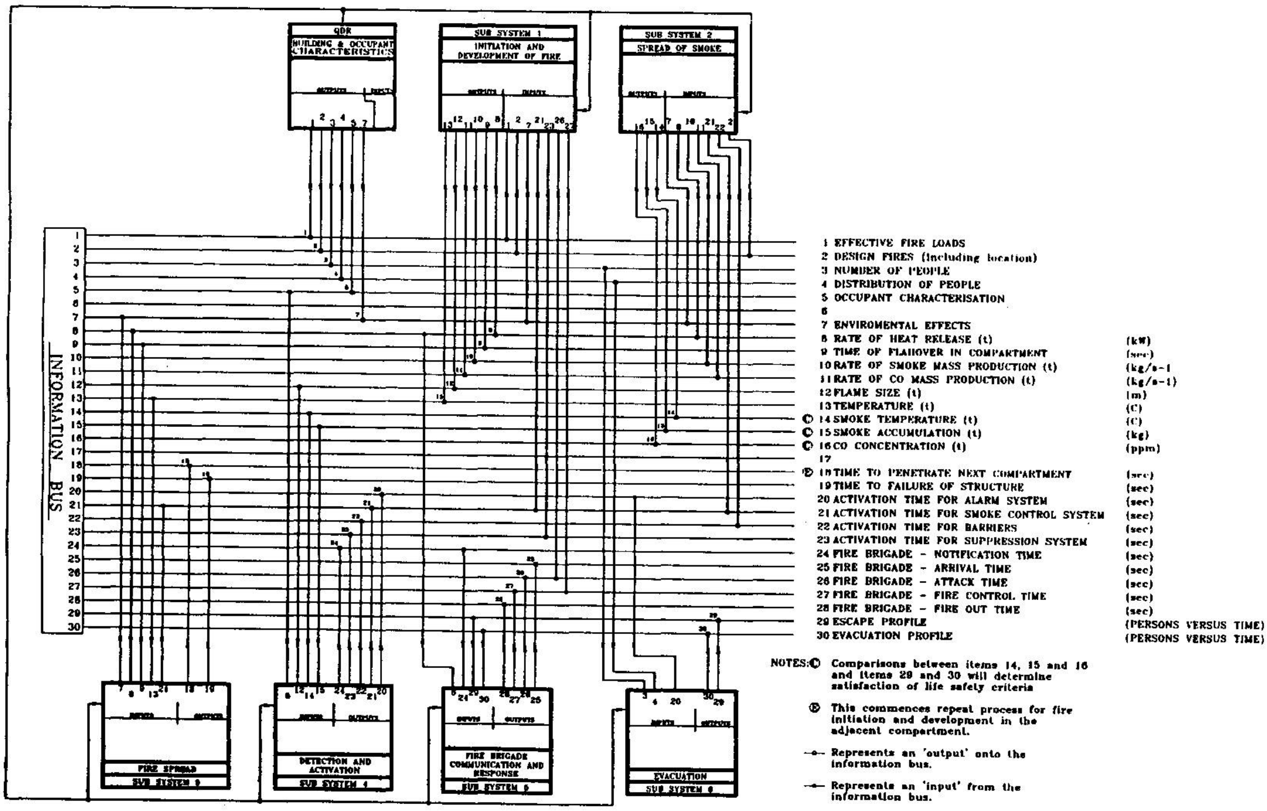


Figure 1. The sub-systems and their independence