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Structural Safety of Long-Span Building Structures

Sécurité structurale des bâtiments de grande portée

Tragwerkssicherheit weitgespannter Hochbauten

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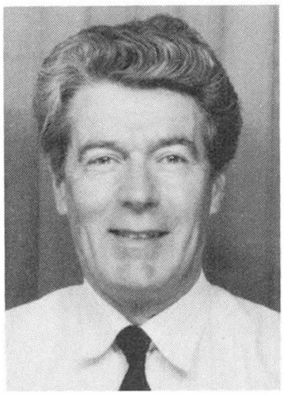

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SUMMARY

In accordance with its brief the Standing Committee on Structural Safety persistently questions the basis for assuming the structures are safe. Long-span structures deserve to be subject to special scrutiny and this paper discusses their distinctive sensitivities. Experience leads to the conclusion that, whilst record of safety of long-span building structures has been good, a vigilant ongoing review of concepts, techniques and materials employed in new long-span structures is necessary. General conclusions for the continuation of this good record are presented.

RÉSUMÉ

Conformément à la tâche qui lui incombe, le Comité permanent de la sécurité structurale examine avec persévérance les bases de la sécurité des structures porteuses. Les ouvrages de grande portée exigent une minutie toute spéciale et l'auteur discute de leurs points sensibles particuliers. Indépendamment d'un excellent bilan de sécurité effectué pour les bâtiments de grande portée, l'expérience montre que les nouvelles constructions requièrent un contrôle permanent des concepts, des techniques et des matériaux utilisés. Des conclusions générales y font suite, en vue de poursuivre cet excellent bilan.

ZUSAMMENFASSUNG

In Uebereinstimmung mit ihrem Auftrag hinterfragt das ständige Komitee für Tragwerkssicherheit beharrlich die Grundlagen der Annahme, Tragwerke seien sicher. Weitgespannte Bauwerke verdienen eine spezielle Sorgfalt, und der Beitrag bespricht ihre besonderen Empfindlichkeiten. Die Erfahrung lehrt, dass ungeachtet einer guten Sicherheitsbilanz weitgespannter Gebäude eine wachsame Ueberprüfung der bei Neubauten eingesetzten Konzepte, Techniken und Werkstoffe nötig ist. Es werden allgemeine Schlussfolgerungen gezogen, um diese gute Bilanz fortzusetzen.

1. INTRODUCTION

Structural safety requires there to be unused margins of stiffness and strength throughout the intended life of a structure. This guards against failure due to changes in loading or material deterioration with time.
The unused margins are influenced by:

- the design concept, assumptions and detailed design;
- the performance of the structural materials and the construction relative to the design assumptions;
- the use of the structure and its actual in-service environment compared to the design assumptions;
- the maintenance of the structure.

In many ways, the behaviour of long-span structures is more sensitive to all these influences than that of shorter spans. The sensitivities and the implications for design, construction and use are discussed in this paper in the light of references by the Standing Committee on Structural Safety to recently constructed long-span buildings in the United Kingdom[1].

2. BACKGROUND TO STRUCTURAL SAFETY

Both the traditional permissible strength margins and the probability - orientated partial factors used in modern limit state design relate only to notional margins. In design these notional margins are applied to idealised structures in simplified environments in contrast to the real structure in its actual environments.

The idealisation (model) of the structure used for analysis purposes is traditionally based on 'safe' assumptions. It usually ignores small or unreliable influences on structural behaviour which are thought generally to contribute beneficially to stiffness or strength. The result is that, from the practical experience of such structures, it is known only that, given the idealised and simplifying assumptions used in design and construction, very few collapses occur. A precise quantified measure of safety in the actual conditions cannot be derived. There is, of course, much more to the achievement of structural safety than refinement of the design model.

Whilst it is rarely possible to quantify precisely the actual ultimate strength or stiffness of a structure it is generally possible to identify hazards. These may occur in the loading or environment or from influences within construction. Such an approach reduces the risk of failure by asking the question "What if?".

In relation to structural loading and the surrounding environment, a value at the extreme of the probability model of loading can be taken. The structure can also be shielded from certain forms of loading, eg explosion, vehicle impact.

In relation to the structure itself, measures include:

- protecting the structure from aggressive actions in the environment. Coatings are used to exclude agents of deterioration, and/or materials which are resistant to deterioration may be adopted;

- aiming for a structure stronger and/or stiffer than basic margins to carry the simplified loads used in design;

- ensuring that any possible structural deterioration could be detected by routine inspection
- using forms of structure with ability to redistribute loads in the event of local failure or damage, generally obtained by providing the structure with a degree of statical indeterminacy.

In addition, measures for quality assurance in the design, construction and maintenance processes aim to give a high probability that what is done yields a safety margin as high or higher than the design intended. These measures should not be used to excuse reductions in partial factors in design but rather should provide a greater assurance that the design assumptions are sound and that the design concept has been totally fulfilled.

The achievement of structural safety is therefore not simply a matter of partial factors used in design, or even just of the design. It derives from consideration and management of all aspects mentioned above. The task is to maintain the margins against 'unsafe' conditions as a result of any of the multitude of uncertainties and hazards which may arise in the life of a structure. Structural safety has to be engineered from beginning to end.

3. SENSITIVITY OF LONG-SPAN BUILDING STRUCTURES

The safety of long-span building structures is particularly important where they are used to accommodate large numbers of people. To ensure their safety the particular sensitivities relating to their size and structural form have to be recognised.

1) With increasing span size, the stiffness and strength properties of the structural materials as opposed to the structure have a decreasing influence on structural response. The characteristics of the structure overall, ie its geometry, become predominant in determining the building's response to its loading environment. The maintenance of the intended structural geometry is affected by two factors, the relative stiffness of components and flexibility overall. Relative stiffnesses of the larger components or sub-assemblies within an overall structure have to be compatible if the structure is to behave as a unit and not be susceptible to distress caused by differential movements or undue stress concentrations. At the same time excessive flexibility of the overall structure or its major components has to be avoided since it may invalidate the geometric assumptions made in the design. Assumptions commonly made are that plane trusses have no lateral distortion and act in the same plane as the applied loads and that compression members are straight. It is more difficult to ensure that these assumptions are valid with long span structures. Secondary stresses arising through connection eccentricities and deformations may be significantly more important with long-span structures.

Ceilings and services suspended from, or rigidly attached to long-span roofs may also be affected by flexure or vibration or give rise to vibrations and lateral loads.

2) In long-span buildings the components are both more susceptible to permanent deformation due to dead loads and more flexible in their response to live load than the shorter components in other construction. The greater flexibility may require special consideration of dynamic performance and fatigue. The combination of permanent deformation and flexibility can have a direct effect on the structural geometry making these structures more sensitive to the presence of structural defects. In roofs, susceptibility to these effects is further enhanced by the increase in thermal movements with roof span (which also may be magnified due to exposure to extreme ambient temperatures) since in buildings generally, unlike bridge structures, bearings and joints are seldom specifically designed to accommodate thermal movement and overstressing

sometimes occurs. In addition, in roofs the structure is usually 'working' nearer to its design resistance than in floors because ratios of dead load to live load are higher.

3) In long-span buildings it is also more difficult to provide the structure with the ability to redistribute loads in the event of local failure or damage. In the event of a local failure in part of a long span, the whole building structure may be potentially at risk. This leads to the paramount need to ensure that such members are more than adequately strong and robust, especially if they are unable to redistribute their load to neighbouring members in the event of failure. The same considerations apply to connections.

It has to be acknowledged that there is a high price to be paid in long-span structures for any increase in self-weight. Additional robustness is difficult to achieve otherwise. Tolerable deviations assumed in design must be carefully prescribed since they affect the transfer of loads between members and the actual stresses experienced.

4. REVIEW OF EXPERIENCE

In the 1970s there were a few collapses of assembly and arena-type structures of modest spans in the UK. Most of these collapses were initiated at inadequate connections or because the structure was inherently unstable, for example, see [2-6]. The inadequacy was sometimes increased as a result of the use of weak or deteriorating materials. The origins of the structural defects associated with these experiences and more recent reports remain relevant. Similar collapses have been avoided in the UK subsequently.

Structural defects arise in one or more of the three phases of a building's history, ie design, construction and use.

4.1 Design

Structural defects have occurred through the adoption of poor design concepts sometimes without clear definition of principal load paths. A lack of competent professional engineering input in design has led to the construction of inherently unstable structures and to defects in major connections The likelihood of design not receiving the appropriate professional supervision has appeared to be greatest where modest span forms of structure, traditionally built with little engineering input, are extrapolated into larger span structures.

Many of the defects identified in the 1970s were associated with inadequate consideration of factors affecting stability and of the connections for strength, stability and movement. Omission or incorrect assessment of loading conditions was a factor in several collapses. More commonly design errors occur in the detailing of connections. Problems arise, for example, due to failure to allow for adequate access to achieve high standards of welding, to permit and ensure effective grouting and to enable thorough inspection subsequently. Explicit and critical examination in design of the essential features of the structure which ensure stability against all foreseeable hazards and close supervision and checking of the design is necessary. This should also eliminate connection defects likely to influence stability.

Other defects have been associated with the quality of the material used and its ability to retain its structural performance in the environmental conditions in the completed building. These defects led to collapse when they occurred in conjunction with stability or connection defects. Thus the incidence of collapses in new construction is likely to be reduced by making sure in design that suitable materials are specified for the environmental conditions. The design must also ensure that realistic environmental conditions are assumed and defined to those responsible for the use of the building.

In the United Kingdom moisture arising from leakage or condensation has been the most important environmental factor aggravating defects in structures. Experience shows that buildings most prone to problems associated with excessive moisture are those with flat roofs. Swimming pools create a particularly aggressive environment. Sealed roof voids allow a build up of condensation, as do large areas of single glazing or poorly insulated walls. Leaks in flat roofs may be due to a number of factors, particularly.

(i) Lack of accuracy achieved on site making the provision of the specified plane surface to shallow falls an impractical proposition for drainage.
(ii) Long-term deflection of components or dynamic movement due to wind action being greater than anticipated in the original design.
(iii) Thermal movement and ageing causing waterproofing seals and membranes to crack.
(iv) Poor maintenance of materials with limited life performance.

In general the result has been for flat roofs to 'pond' causing additional load and creating more local deflection, and for the water to seep eventually through the barriers onto the structural components. Long-span flat roofs are particularly sensitive to these factors. Leaks may then occur anywhere in the roof area. If the source of moisture is mainly due to condensation the locations found to be affected most are the bearings and joints at the ends of beams around the periphery of the building. Long-span flat roofs need to be designed to stringent requirements and with increased falls in order to reduce the risk of moisture promoting structural deterioration.

Long-span pitched roofs may experience very irregular snow loading. In particular heavy accumulations can occur at the eaves.

4.2 Construction

Some defects have arisen when suppliers of prefabricated components or sub-assemblies have acted as sub-contractors to the main contractor and the suppliers were inexperienced or were changed without the engineer's approval. These organisational arrangements have resulted in some instances in the quality of the product supplied being inferior or in the supplier being not fully aware of the context in which his product is to be used.

The likelihood that structural defects may be built into any building is influenced by the supervision employed on the site during construction, bringing into question the role of the main contractor and the client's site representative. There is no doubt that the ability and conscientiousness of the main agent, the resident engineer and local building control officer, have a profound influence on the detection and correction of defects. A proportion of defects have arisen as the result of the use of low quality materials outside the specification and poor control of workmanship on site. Omission of essential components or connections, defective assembly of connections, the use of components of incorrect size and the production of poor quality concrete on site have been factors contributing to collapses. Such defects appear to have arisen sometimes because organisational responsibilities were not clearly defined especially in sub-contracting of major sub-assemblies where divided ill-defined responsibilities for design checking and construction supervision occurred.

Factors referred to in 4.1 Design have a profound influence on construction effectiveness, eg. in welding, grouting and packing. Where these are not made as designed and where envisaged tolerances are exceeded, serious loading stresses can occur. Checking should therefore be progressive and not be left too late for adjustments to be made.

4.3 Use

Some structural defects leading to collapse of buildings with long-span roofs have arisen as a result of:

- Poor maintenance
- Substantial increases of the dead load on flat roofs caused by additional layers as a means of repair to waterproofing.
- Roofs overloaded by additional services.
- Failure to maintain the weatherproofing of flat roofs.
- Failure to maintain dry conditions in timber roofs.

The trend in the construction of arenas and stadia in recent years has been towards accommodating a wider range of facilities in increasingly large enclosures with ever greater spans. Crowd loadings and fire precautions have received far more public attention than structural adequacy. The need for engineering all aspects of the life of these large structures is clearly apparent. Innovation and extrapolation have been necessary to achieve structures worthy of the era of space age technology. There have been no reported fatalities due to the collapse of permanent arena or stadia structures, but continued vigilant inspection by knowledgeable engineers is advisable. Good access should therefore be provided by design. This will not only improve the quality of inspection but will reduce its cost.

Some striking long-span building structures have been successfully completed recently in the UK. An example is shown below in Figure 1.

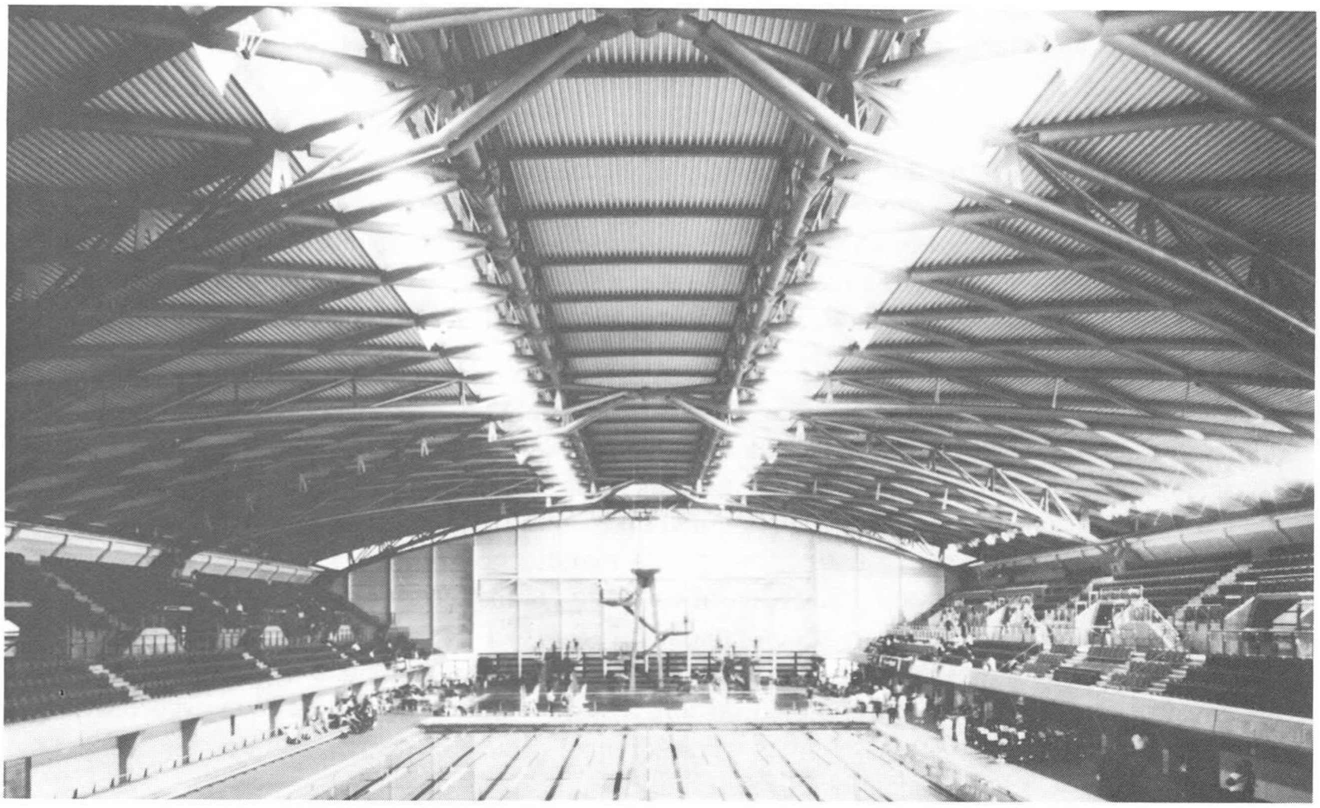

Figure 1. Swimming Pool, Ponds Forge, Sheffield (by courtesy of Ove Arup & Partners)

These structures are of substantially longer span and span/depth ratio than the examples of failure previously mentioned. They have been fully engineered to high standards throughout design and construction. The particular sensitivities of long-span structures have no doubt been recognised. It is noted that, especially in stadia structures, the structural form involves large-span trusses (120m or more) or long cantilevers (40m or more) which may be subject to excitation by wind action.

Roof structures may comprise statically determinate primary elements with limited redundancy to redistribute loading in the event of single element failure. Such long-span structures appear to be at the present limits of size for beam-and-column forms of structure. Where longer-span buildings are required, alternative forms possibly incorporating major tension cables, eg. the Georgia Dome in Atlanta, may be used.

General conclusions relating to long-span building structures are discussed below.

5. DESIGN

In view of the greater sensitivity of long-span building structures, the generalised criteria from codes prepared for normal span structures may not be sufficiently strict or comprehensive. It is necessary to work from first principles and to use realistic design assessments of environmental conditions. The structural material specified must be durable or protected where the environment is likely to be aggressive, eg in swimming pool buildings.

There are several ways of making design criteria more stringent. It is usual in the initial design of structures to assume connections are fully effective. Design analysis often does not take account of possible failure of connections but rather concentrates on the anticipated structural form. No checks are made on the influence of realistic connection performance on the behaviour of the whole structure. Such checks on the sensitivity of long-span structures to loss of connection effectiveness and the use of larger margins of safety at critical connections are ways of introducing appropriately strict design criteria.

The requirements for inspection and examination of a long-span building structure have implications for the design. Clearly these operations are facilitated if the structure is visible and easily accessible. Likewise structural safety is more likely to be achieved if the form and type of structure is one which would give early visual signs of local distress or defects should unforeseen damage or deterioration occur. Essentially it is an advantage for as much of the structure as possible to be easily visible and not hidden. These considerations are often compatible in modern long-span building structures with the design for the architectural expression of the structural form.

There should be competent independent checking of the structural design. The checks need to make sure, in particular, that possible hazards and modes of failure are identified and that either the design safeguards the structure against them or that the structure is protected from the hazard.

6. CONSTRUCTION

In view of the greater sensitivity to structural defects of buildings with long-span structures, it is especially important that construction is to a high standard and all defects avoided at that stage. Particular attention should be paid to those parts of the structure which will be hidden on completion to ensure that they are as the design intended.

The closest possible supervision of construction is needed. This should give particular attention to any elements critical to stability and safety. The client's engineer or an independent engineer inspecting during construction should be able to provide certification on completion.

7. SUPERVISION AND INSPECTION

Professional engineering input to inspection is needed even where spans are modest. Appropriate professional engineering supervision and inspection is therefore especially important in design of long spans.

8. USE AND MAINTENANCE

Regular maintenance inspection and structural examination are needed to assure future safety. A permanent and comprehensive record should be kept and reviewed by a suitably qualified engineer.

A distinction is made here between normal maintenance inspection and structural examination. Normal maintenance inspection is assumed to be visual only from points of easy access. Structural examination is a higher level of inspection undertaken by a professional engineer making a full structural appraisal. Such examinations should be regularly scheduled during the life of a long-span building structure.

Structural examination is normally visual in the first instance and includes critical examination of the design. It also involves closer inspection of the structure by access to roof and ceiling spaces or, if necessary, exposure of critical components to allow visual or other examination.

It is particularly important for buildings with long-span roofs to be maintained so that the environmental conditions and the dead load are not allowed to depart substantially from the assumptions of the design.

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