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« CONCRETE STRUCTURES SUBJECTED TO TRIAXIAL STRESSES »
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The U.K. Experience in the Analysis and Design of Triaxially Stressed Concrete Structures Supported by Model Investigations with Particular Reference to Prestressed Concrete Pressure Vessels

Le support des essais sur maquettes dans l'analyse et le projet de structures en béton chargées triaxialement, avec référence en particulier aux caissons pour réacteurs nucléaires. Expériences réalisées dans le Royaume-Uni

Die Erfahrungen im U.K. in Analyse und Design von dreiachsigen Spannbeton-Konstruktionen unterstützt durch Modelluntersuchungen unter besonderer Berücksichtigung von Spannbeton-Druckbehältern

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1. INTRODUCTION

Most concrete components and structures are in a state of triaxial stress in one form or other although, for practical design, gross simplifications have to be made:

(i) to reduce design time and cost

(ii) since a knowledge of triaxial behaviour is not generally available to designers

(iii) since appropriate methods are not readily available

(iv) since the external forces cannot always be defined with precision

However, for complex structures, such as dams, pressure vessels, tunnels, offshore oil drilling platforms, a greater understanding of the triaxial behaviour is required.

Over the last fifteen years in the U.K. extensive research and development has been carried out on material properties, methods of analysis and model testing for such structures. In the case of prestressed concrete pressure vessels for nuclear power stations, the stringent demand for reliable information as to the behaviour of these critical structures both as regards their safety and their operation performance has required exhaustive investigations on many fronts. Aspects covered include material behaviour throughout the operating life of 30 years, overall and localised behaviour of the vessel by model testing, and full instrumentation and observation of the final structures during proof pressure testing, commissioning and operation. The authors have been closely involved in the design, development and construction of a number of vessels both in the U.K. and overseas.

In attempting to cover for the U.K. the major structural situations where triaxial stress states are significant, the authors realise that the items presented may not do justice to the overall effort by universities, government and commercial establishments in the various fields. In the paper only selected aspects have been included to demonstrate the width of progress.

This has involved examining the following main areas of activity:

(i) material research

(ii) methods of analysis

(iii) model and component testing

(iv) observation of the structures' behaviour

(v) current design methods

All these factors should be assessed in order to simplify or improve design methods or to enable more advanced structures to be built with confidence. Further, each of the above factors has to deal with two main loading conditions, the operating condition and the overloaded state.

In both categories an understanding of any triaxial stress situation may require a knowledge of the following parameters:

(i) short term elastic/plastic behaviour

(ii) long term, creep and shrinkage performance

(iii) response to dynamic, cyclic and random loads

(iv) the behaviour at ambient or elevated temperature

The following "matrix" chart encompassing the various components of the design process, has provided a background to the following sections covered in the paper: materials research, confined concrete components, pressure vessels, dams, tunnels, etc.

Materials Analysis Models Field Data Design	Short/Long Term Loading	Static/Dynamic Loading	Operational/ Overload States	Normal/Elevated Temperature

DESIGN DEVELOPMENT 'MATRIX'

2. FUNDAMENTAL RESEARCH

2.1. Triaxial Loading

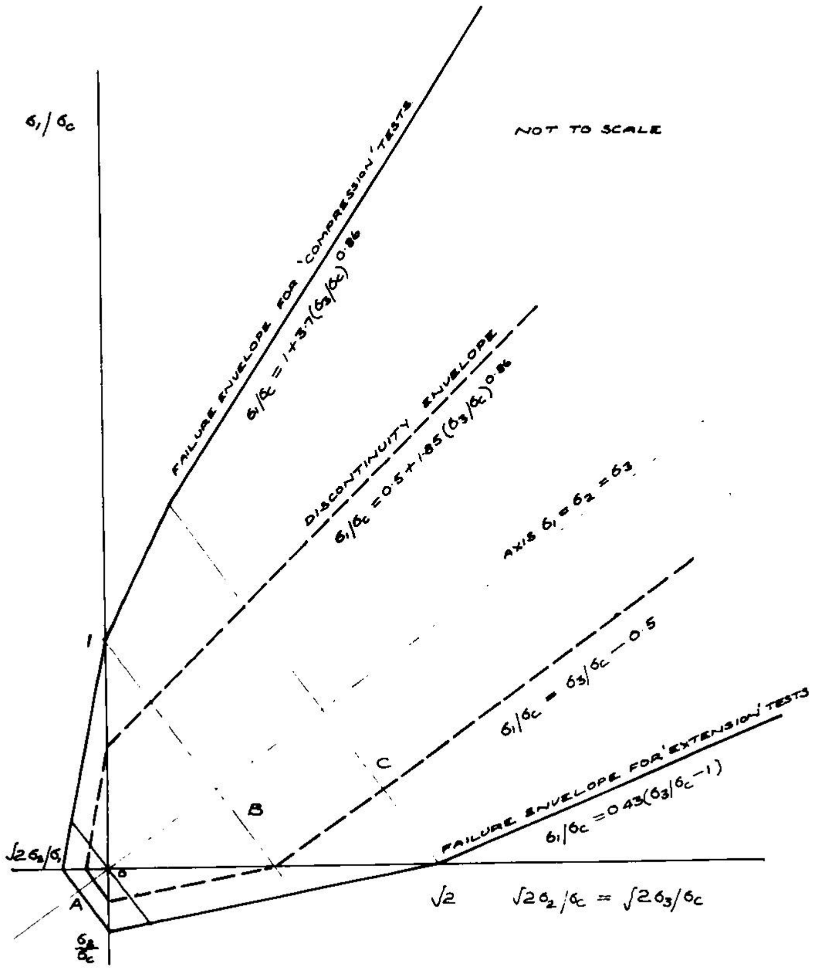
The stress/strain behaviour of concrete up to failure under short term loading has been extensively investigated by Newman and Newman(1 & 2) primarily using biaxial compression/tension and hydrostatically contained triaxial specimens. The experimental programme covered mortar, artificial, and natural aggregate concretes.

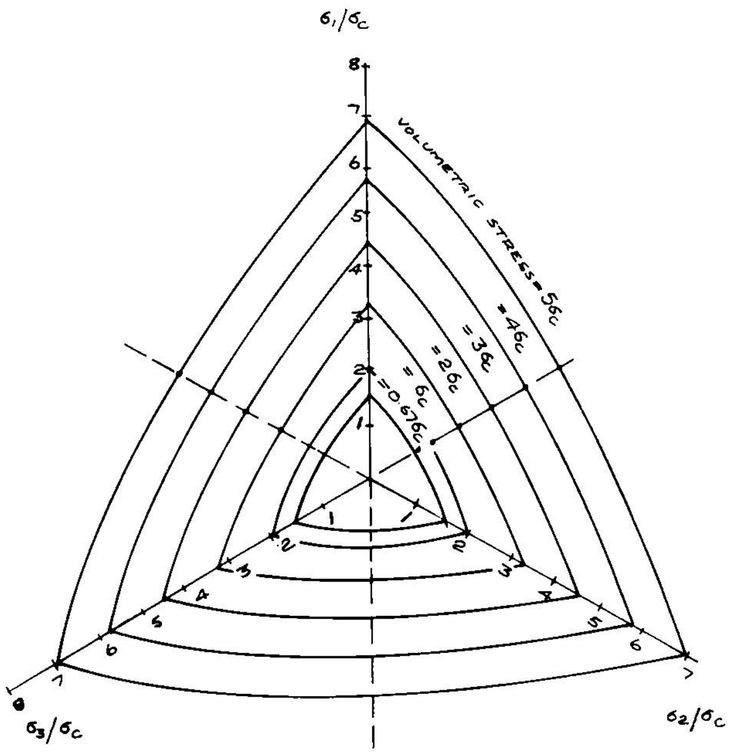
This research could provide valuable basic data for analysis programmes involving non-linear triaxial behaviour to failure.

From their work, together with comprehensive analysis of the results of other researchers, a triaxial compression/tension failure representation (Fig. 1) was produced initially including the level of onset of major internal dislocation of the

FIG. 2

ULTIMATE AND DISCONTINUITY FAILURE SURFACES FOR CONCRETE (NEWMAN & NEWMAN)





POSSIBLE DESIGN CHART FOR ULTIMATE STRENGTH FAILURE CONCRETE IN THE TRIAXIAL COMPRESSION REGION (NEWMAN & NEWMAN) material, the discontinuity level, which was considered also to be of importance to the long term sustained and cyclic loading stability of the material. Methods of utilising the triaxial compression/tensile performance for design have been developed (Fig. 2.)

Another comprehensive analysis of published data on the triaxial strength of concrete has recently been reported by Hannant(3) from which he derived simplified design nomograms for handling combinations of multiaxial stress to predict failure.

Perhaps the above work highlights the care needed in utilising the triaxial strength of concrete where one stress is relatively low, and thus high biaxial states occur. The strength gain over the uniaxial compression value is both marginal and uncertain. This may limit its application to that in which low deviatoric stress states exist.

Shear

The above work has not considered the behaviour of concrete in shear under multiaxial stress states, of importance particularly in concrete pressure vessel design. Intensive experimental work by Garas and Langan(4 & 5) has shown that deep sections of various geometric and restraint states (Fig. 3) give ultimate shear strengths several times greater than for normal, low restraint, shear conditions (Table 1 and Fig. 8b).

TABLE 1 Nominal Shear Stresses in Beams and Slabs as a Function of Compressive Cylinder Strength of Concrete (f_c)

Nominal Shear Stress at Failure $= K \times \sqrt{f_c}$ (f_c in N/mm^2)

Type of Element	K
1. Beams a. Shallow unrestrained b. Deep restrained (span/depth = 2.5)	0.17 - 0.33 1.33 - 1.58
2. Slabs a. Shallow unrestrained b. Deep restrained (span/depth = 2 & 2.5)	0.50 - 0.75 1.50 - 2.00
3. Small Discs (span/depth = 1 to 3) a. Unrestrained b. Restrained	 0.83 - 1.67 2.25 - 5.17
4. Anchor Block Models	4.42 - 7.42

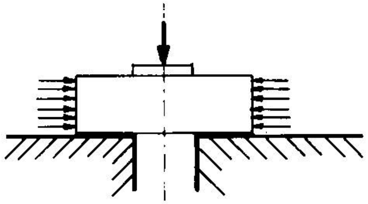
Even in tensile zones, aggregate interlock was believed to contribute to the ultimate shear strength although large deformations along cracks were recorded.

2.2. Creep

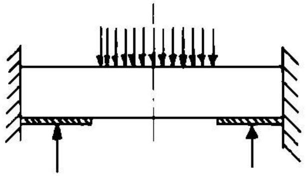
Sustained long term loading effects on concrete deformation behaviour, covering the working stress levels used in structures, have been extensively investigated particularly in relation to concrete maturity for normal and elevated temperature conditions by Browne and Blundell(6). Their experimental work was confined to uniaxially loaded concrete since published data available had demonstrated that generally Poisson's ratio could be regarded as constant under multiaxial sustained load and within the range of 0.15 - 0.23 for different states of stress including elevated temperature (Fig. 4).

FIG. 3

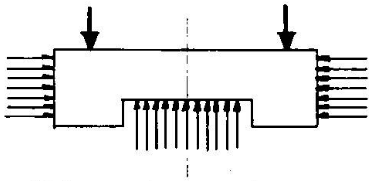
DIFFERENT STRUCTURAL FORMS SUBJECTED TO BIAXIAL COMPRESSION AND SHEAR
(GARAS & LANGAN)



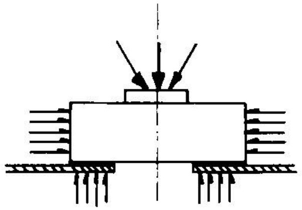
(i) SMALL DEEP ELEMENTS



(ii) RESTRAINED DEEP BEAMS



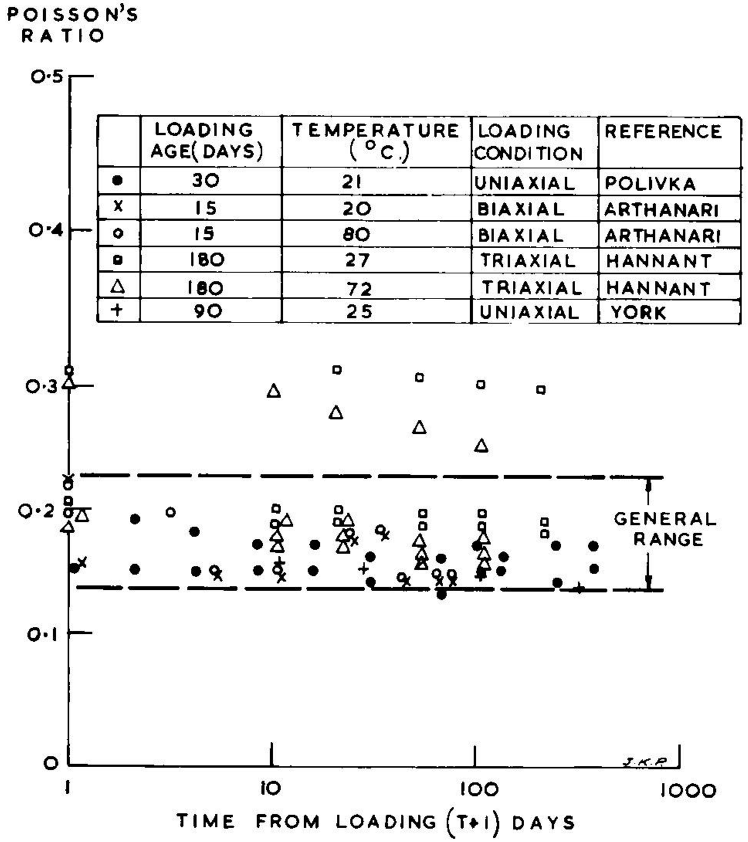
(iii) PILE CAPS OR END CLOSURES



(iv) CONCRETE ANCHOR BLOCKS

FIG. 4

POISSON'S RATIO FOR SEALED CONCRETE UNDER UNIAXIAL AND MULTIAXIAL SUSTAINED LOADING CONDITIONS.
(BROWNE & BLUNDELL)



They also showed from long term tests (Fig. 5) the close similarity of creep for different concretes, provided the elastic modulus of the aggregate exceeds 10×10^6 psi (7×10^4 N/mm^2). This enables the designer to use one set of standard creep data for such concretes.

Recently Illston and Jordaan(7) have confirmed the similarity of creep Poisson's ratio to the elastic value for uniaxial, biaxial and triaxial stress states (Fig. 6) and have developed a method of handling elastic and creep deformation under changing multiaxial stress states with time. Illston and Sanders(8) have also investigated the effect of temperature change under sustained load for mortar using torsionally loaded specimens. This work showed that temperature change induces only an initial increase in the creep rate, although the maximum period of loading reported was 3 months only.

The effect of cyclic loading (585 cycles/min) on creep and delayed failure has been investigated by Whaley and Neville(9) showing that cycling can increase the non-elastic time dependant deformation of concrete.

2.3. Analysis

The exhaustive development of analysis methods based on the finite difference, finite element and dynamic relaxation techniques have provided useful tools to handle the elastic behaviour of 3-D stressed structures covered in this paper. Increasingly larger problems have been analysed facilitated by the introduction of substructuring techniques and the ready availability of finite element packages on a bureau usage basis using large core computers.

Current trends in analysis methods have been towards non-linear applications to deal with both geometries (large deflection, buckling) and material properties(10) (plasticity, creep, crack propogation etc.) Lewis and Irving(11) and England(12) have developed methods of analysis to predict time dependant behaviour incorporating temperature, for concrete pressure vessels. However, the authors are not aware of the extent to which these methods have been applied to vessel design, the effective modulus approach still being generally in use.

3. CONFINED CONCRETE COMPONENTS

Concrete Filled Tubes

Extensive work by Sen, Chapman and Neogi(13 - 15) on testing and developing design methods for concrete filled steel tubes (Fig. 7a) with axial and eccentric loads, showed that with height/diameter ratios over 15, the effect of biaxial passive restraint provided by the steel tube was negligible due to the dominating effect of buckling. However, tests on concentrically loaded concrete filled stubb columns showed that for diameter/tube wall ratios from 17 to 37, only after the longitudinal stress of the steel has approached its compressive yield stress does the restraining effect on the concrete become operative (Fig. 8a). The strength of the concrete was nearly 2 times its uniaxial value and the column load was up to 1.6 times the sum of the uniaxial compressive strength of the steel and concrete.

Utilisation of this passive restraint technique of concrete in tubes so far in normal construction appears to be limited, particularly since in buildings, problems such as end connection design, have not as yet been resolved nor the performance of such columns under fire. However, applications could include bridge support columns and piles and limited information available suggests that this appears to be so.

FIG. 5

THE EFFECT OF AGGREGATE MODULUS OF ELASTICITY UPON CREEP OF CONCRETE. (BROWNE & BLUNDELL)

CREEP ASSUMED AS UNITY FOR $E_{AGG} = 0{\cdot}69 \times 10^5\ N/mm^2$.

COARSE AGGREGATE CONTENT = 45 TO 55 % BY VOLUME.

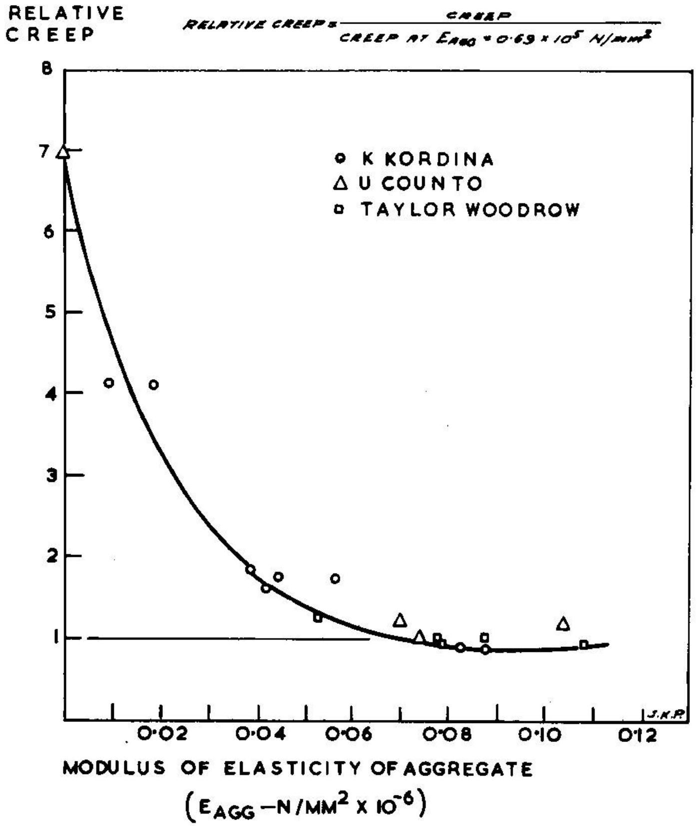
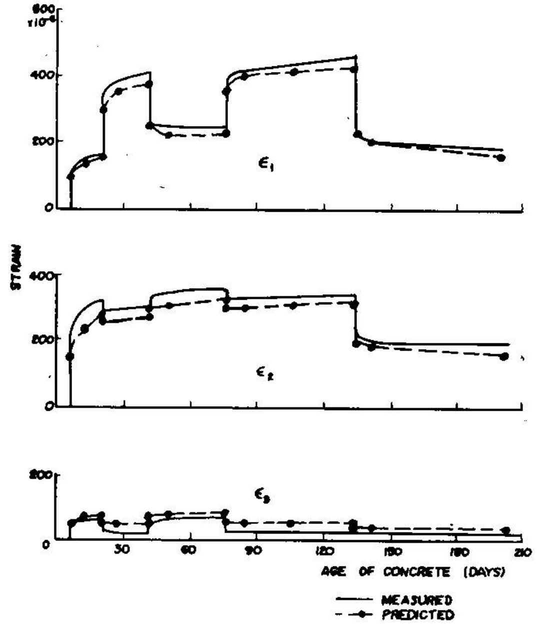


FIG. 6

PREDICTION OF STRAINS DUE TO A VARIABLE TRIAXIAL STRESS SYSTEM (ILLSTON AND JORDAAN)



CONFINED CONCRETE COMPONENTS.

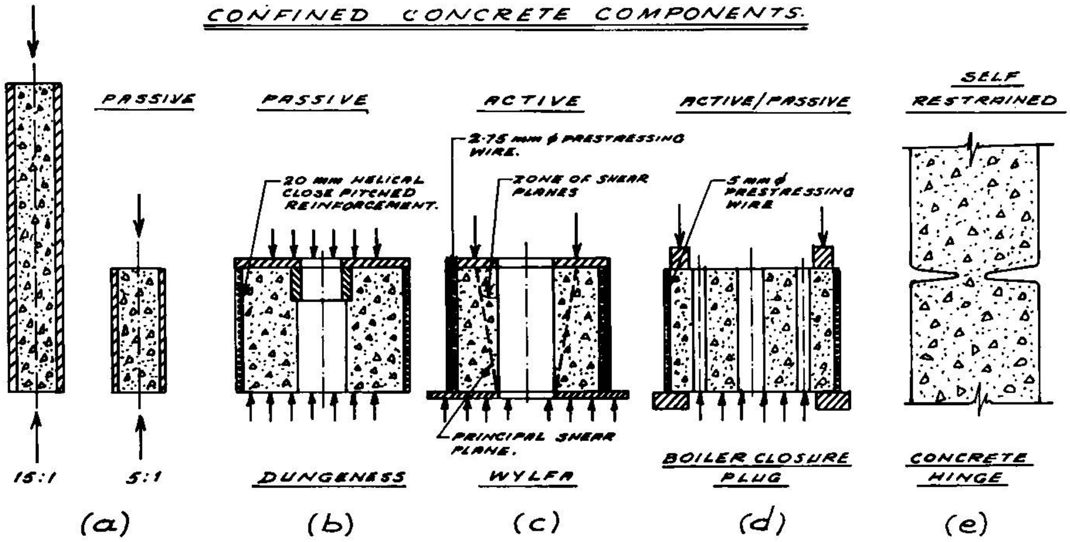


FIG. 7

EFFECT OF HOOP RESTRAINT ON THE AXIAL AND SHEAR STRENGTH OF CONCRETE.

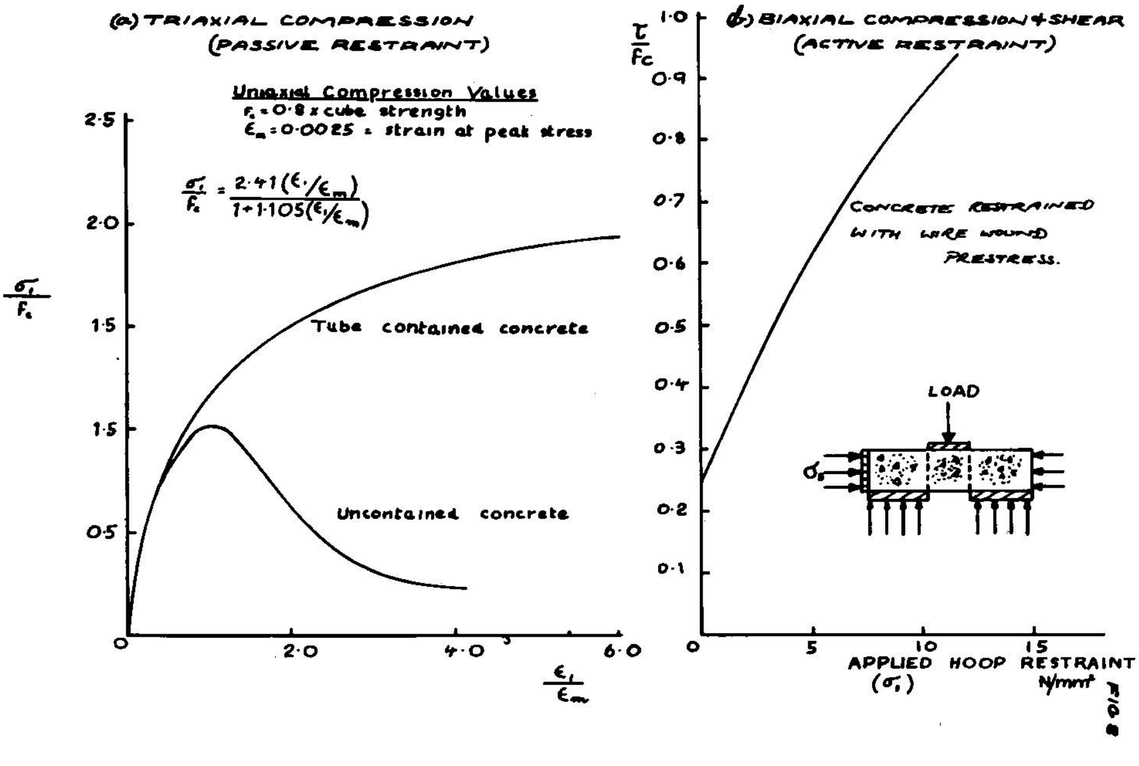


FIG 8

Prestress Anchorages

The authors are not aware of any recent development of further practical design methods for prestress anchorages where high tensile splitting stresses arising from excessive bearing load may be controlled by reinforcement. Perhaps re-examination of the experimental work of Roe and Zielinski(16 & 17) might be fruitful in the light of current development of multiaxial concrete behaviour theory and analysis techniques.

A particularly successful application of the passive restraint technique is in the design of the prestressing bearing plate assembly for the two concrete pressure vessels for the Dungeness 'B' nuclear power station(18). Here, a precast concrete block for the 660 tonne tendons (Fig. 7b) is contained to withstand the high prestress loads by a continuous winding of 19 mm dia. high tensile deformed bar, the unit subsequently being embedded in the vessel concrete. Considerable development work, including long term loading tests, were carried out to confirm the adequacy and safety of the component.

The limitation of the passive restraint technique is that accumulation of strain is required before the benefit of the potential restraint is mobilised.

3.2. Active Restraint

A more direct method is to apply an active restraint to concrete in the form of prestress. Again, the main use so far has been as prestress anchorage blocks for large tendons (584 tonne) for the two pressure vessels for the Wylfa nuclear power station(19) which has been in operation for four years.

Fig. 7c shows the features of the cylindrical block wound with high tensile 2.65 mm dia. wire to a stress of 1300 N/mm^2. The mode of shear failure as shown in Fig. 7c was established by overload tests on 1/3 scale models and nominal strengths of the order of 37 N/mm^2 were achieved (i.e. 20 x the conventional shear strength).

Both short and long term elevated temperature tests were carried out on the full size blocks showing acceptable prestress relaxation, predictable creep using uniaxial specimen data and no significant influence of a sustained temperature of 40°C. No fully acceptable method of analysis of the design was available at that time.

The active restraint combined with the passive restraint has been recently introduced on a highly critical component for the Hartlepool and Heysham pressure vessels which is the closure for the boiler cavity in the pressure vessel walls (Fig. 7d). A full description of the details and the support test work are given by Garas at this Seminar(20).

3.3. Concrete Self Restraint

The use of concrete itself to provide its own restraint to axial and non-axial loads has been employed successfully for many years in concrete hinges (Fig. 7e) for many bridge structures and recently for precast tunnel linings(Section 6.3).

Tests on various hinge configurations were carried out by Base(21) both as regards their load bearing and rotation capability. Reinforcement through the throat was thought to be unnecessary even under shear conditions. Compressive strengths several times the concrete cube strength were achieved without causing crushing of the concrete.

4. CONCRETE PRESSURE VESSELS

4.1. Introduction

In the U.K. extensive programmes of work have been undertaken to develop a number of prestressed concrete pressure vessel (P.C.P.V.) designs for nuclear power stations. This technology started in about 1959 and since then there have been considerable advances which are indicative of the extensive research and development activity which has been devoted to this field. The studies have been concerned with the fundamental problems involved and have utilised reasonably well established techniques such as model and computer analysis. One outcome of this technology was the introduction in 1973 of the British Specification for Prestressed Concrete Pressure Vessels (22).

A considerable amount of this work has also been reported in International conferences(23 - 26) and technical journals. It is only possible in this paper to give below a brief account of the total development work, related to analysis, design research and field observations.

4.2. Vessel Description and Design Conditions

Fig. 9 shows the layouts of the vessels which were completed or are being built in the U.K. The main features of these vessels, the method of analysis adopted and the type of models constructed and tested for each vessel are summarised in Table 2.

Basically, the vessels are three dimensional bodies of simple geometry, but they are made complex by the requirements for steps, penetrations and ribs, causing a variety of stress concentration conditions. Current techniques of analysis depend upon setting up various mathematical models which are capable of numerical solutions.

As a standard procedure, each vessel is designed for the following conditions:

(1) A linear elastic phase which covers all the normal operating conditions:

- (a) construction, prestress, commissioning including the proof test.
- (b) early and long term (30 years) operation including intermittent reactor start up, shut down and fault conditions.
- (c) local stress concentrations and prestressing anchorage stresses.

In addition to compliance of a vessel to permissible stresses, the vessel also has to cater for strain compatibility with a steel internal liner and overall movement tolerances in relation to reactor components. The above conditions can be thoroughly examined by readily available analysis programmes.

(2) An ultimate load analysis which involves large deflection with small increases of pressure where the structure behaves as a mechanism.

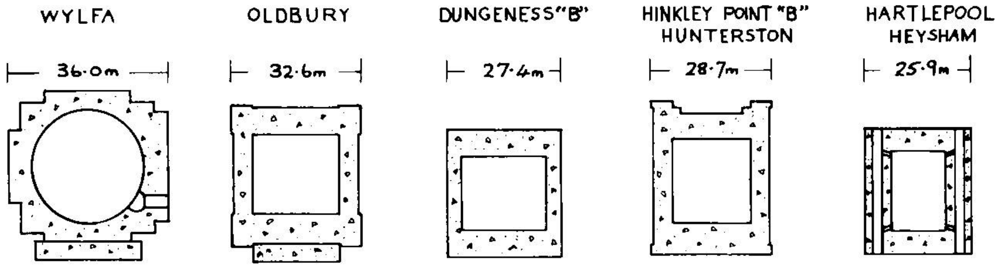
An adequate prediction by either theoretical or model analysis of overload behaviour is essential to confirm that a proper margin of safety exists for normal loads, currently set at 2.5 times the design pressure(22).

4.3. Design and Analysis

As described in Table 3, basically two methods of analysis, which account for 3-D stresses are used:

- (i) finite element analysis(27)
- (ii) dynamic relaxation(28)

UNITED KINGDOM PRESSURE VESSELS

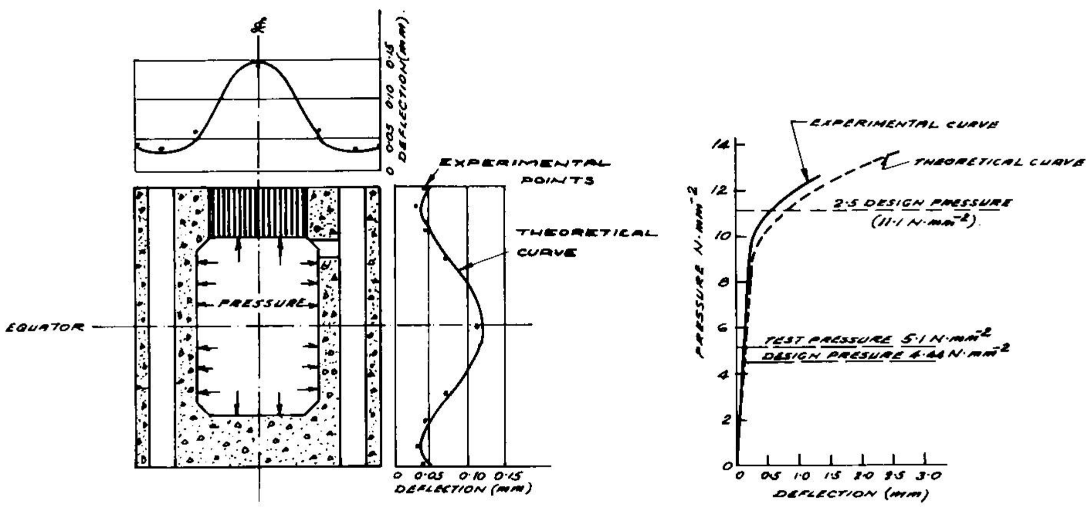


No.		WYLFA	OLDBURY	DUNGENESS "B"	HINKLEY POINT "B" HUNTERSTON	HARTLEPOOL HEYSHAM
1	POWER OUTPUT	590 M.W.	300 M.W.	607 M.W.	625 M.W.	622 M.W.
2	DESIGN PRESSURE	423 P.S.I.	385 P.S.I.	520 P.S.I.	615	644
3	MINIMUM FACTOR OF SAFETY	2·65	3·0	2·5	2·5	2·5
4	VOLUME OF CONCRETE	27,700 CU. YDS	24,288 CU. YDS	16,400 CU. YDS (EST.)	22,600 CU. YDS	15,180 CU. YDS
5	TEMPERATURES °C					
	a). MEAN GAS COOLANT	331	331	485	483	467
	b). CONCRETE INTERNAL	45	55 - 60	55	70	55 - 60
	c). CONCRETE EXTERNAL	30	25 - 30	25	—	30 - 35

FIG 9

PCPV. MODELS: TYPICAL CORRELATION BETWEEN THEORY AND EXPERIMENT.

(LANGAN, O'FLYNN AND WELCH)



EXTERNAL DEFLECTIONS AT 4·41 $N \cdot mm^{2}$ PRESSURE.

EQUATOR DEFLECTIONS VS. PRESSURE.

FIG. 10

TABLE 2 - Summary of Development Work on U.K. Pressure Vessels

Vessel	Organization	Method of Analysis	Model Analysis			
			Type of Model	Scale	No. of Models	Study of
Wylfa	B.N.D.C.	2D - Dynamic relaxation	Spherical PV	1/12	1	E O F T U
	T.W.C.		Spherical PV	1/40	1	E O U
Oldbury	T.N.P.G.	2D - Finite difference and	Cylindrical PV	1/8	1	E O F T U
	McAlpine	dynamic relaxation				
	C.E.G.B.	2D - Finite element	Cylindrical PV	1/8	1	E O T U
Dungeness 'B'	A.P.C.	2D - Finite difference	Cylindrical PV	1/10	1	E O U
			Cylindrical PV	1/26	1	O U
			Isolated End Slab	1/26	1	O U
			Isolated End Slab	1/72	1	O U
Hunterston 'B' &	T.N.P.G.	2D - Finite elements	Cylindrical PV	1/10	1	E O
Hinkley Point 'B'	McAlpine					
Hartlepool &	B.N.D.C.	3D - Dynamic relaxation	Cylindrical			
Heysham	T.W.C.	3D - Finite elements	Multicavity PV	1/10	1	E O
			Isolated End Slabs	1/24	15	E O U
General	U.K.A.E.A./I.C.	3D - Finite elements	Spherical PV	1/12	1	E O T U
	U.K.A.E.A. (Foulness)		Cylindrical PV	1/20	10	F U
	G.E.C. - Simon Carves		Cylindrical PV	-	1	E O T U
	T.W.C.		Cylindrical PV	1/20	1	E O F T
	T.W.C.		Cylindrical PV	1/40	2	E O
Future H.T.R.	B.N.D.C.		Cylindrical PV	1/40	4	E O U
	T.W.C.		Isolated End Slabs	1/26	1	E O U
				1/8	3	E O U
	T.N.P.G.		Cylindrical PV	-	-	-
	McAlpine					

K E Y

B.N.D.C.	=	Nuclear Design & Construction Limited	E	=	Elastic response
T.W.C.	=	Taylor Woodrow Construction Limited	O	=	Overpressure
T.N.P.G.	=	The Nuclear Power Group	F.	=	Fault condition
McAlpine	=	Sir Robert McAlpine & Sons Limited	T	=	Temperature
A.P.C.	=	Atomic Power Construction Limited	U	=	Ultimate load
C.E.G.B.	=	Central Electricity Generating Board			

In the early development of the design of some of the vessels, the application of these analytical tools was limited by the size of computer available. In recent years, the availability of greater capacity computers has encouraged the continued development and application of both techniques.

Extensive work in the application of finite element analysis to P.C.P.V.'s have been carried out at a number of research centres, particularly at the Central Electricity Generating Board's Berkeley Nuclear Laboratories and the University of Swansea. Some of this work has been reported by Lewis et al(11) and at this Seminar by Zienkiewicz et al(10).

The determination of the ultimate pressure of current vessels has so far been only based on simplified analytical methods. Usually the location of principal hinges, in the case of cylindrical vessels, or major crack patterns in the case of spherical vessels, are determined by the observation of models and theoretical analysis, based on the principle of least work(29 & 30).

In the case of end slabs in cylindrical vessels, where the top slab contains multiple penetrations, the designer has only partial ability to analyse the mechanisms of shear failure. In most cases, as shown in Table 2, safe design is achieved by extensive model testing of this area of the vessel(5 & 31).

4.4. Models

Table 2 shows that at least 48 realistic vessel models up to 1/8 scale full size and end slab models have been tested over the last 15 years in the U.K.

These have been subjected to a range of operation and overload conditions including load and thermal cycling and were primarily related to specific vessel designs.

The purpose of a vessel model was to verify the elastic state and to confirm that the vessel would meet the specified overpressure requirement. Frequently these models were pressurised in excess of the specified requirement without significant damage.

In general terms, comparison between predicted and measured behaviour was close (29, 32, 33) (Fig. 10) although the elastic property of the model concrete required modification in a number of cases.

Instrumentation of both model vessels and end slabs was extensive and results have been generally published. The information has provided already reference data for analysis development (11).

Continuing change in vessel geometry and design together with the concern for the safety of such structures will inevitably demand further testing of large scale physical models in the future to confirm the behaviour of the structure and its reserve of strength. Even the development of powerful analytical tools to handle, for example, ultimate load analysis will not, the authors believe, be sufficient to replace such models.

4.5. Observations on Constructed Vessels

All P.C.P.V.s constructed so far have been subject to a cold proof pressure test normally at 1.15 x the design pressure. Since the Central Electricity Generating Board has insisted on each vessel being comparatively instrumented (e.g. about 400 embedded strain gauges) to record temperature, strain and overall movement, this facility has enabled their design and active performance to be correlated. Published data(34 & 35) on the proof pressure tests showed very close correlation between the two.

For the commissioning heating/cooling runs and early reactor operation, so far reasonably satisfactory prediction by design has been accomplished(11 & 36).

However, it should be emphasized that the interpretation process for instrumentation data from embedded strain gauges etc., in the pressure vessels is an extremely difficult process frequently underrated since reliability of data and its effective interpretation depends on considerable attention to all aspects involved, including supporting long-term concrete property data, the realistic calibration of gauges for concrete creep and proving trials to simulate long term gauge durability at elevated temperatures. Careful selection of gauge location is required in relation to analysis grids in areas where reasonable strain magnitudes will be detectable (i.e. no strain change does not mean no stress).

5. CONCRETE DAMS

5.1. General

Dams are generally designed for a number of loading cases including water pressure, gravity loads and temperature variation, and in some cases earthquake shocks. Furthermore, the effects of uplift and time have to be considered.

A very active research programme into the design and analysis of selected forms of arch dams (Fig. 11) was initiated by a number of British Universities with the assistance of practising engineers. This work was fully reported in a symposium held in London in 1968(37) and is summarised in Table 3.

The table shows that considerable effort was devoted to the basic dam shapes selected and that a number of computing methods were developed. Hewever it has been stated that such methods have not been fully utilised by the practising engineer due to the problems of digesting the methods and the fact that he still has to assume elastic behaviour of the ground and dam materials.

A review of this work and performance of the analysis methods was presented at the 1970 Congress on Large Dams in Montreal(38).

Recent work has tended to move away from model testing to improve stability and accuracy of theoretical analyses (Universities of Southampton and Wales) and to developing suitable methods for handling non-linear behaviour and ground variability (Bristol, Wales). Generally, it is now possible to predict temperature effects, gravity and seismic loads with sufficient confidence without model analysis.

Although only a limited amount of model testing is at present underway (e.g. dynamic water/structure interaction at Bristol University) it is considered that theoretical studies on variable foundation conditions (Imperial College) could well be supported by back-up model tests.

5.2. Seismic Loading

For dams in earthquake areas, seismic stresses have to be superimposed on to static stresses causing the structure to be loaded more severely than at any other time. The accurate prediction of possible seismic loads are therefore a matter of great significance in determining the safety of the design.

In one investigation(39) a check was made on conventional methods of earthquake design and the Hendrik Verwoerd Dam on the Orange River, South Africa, was used as a basic model. The finite element method of analysis was adopted. A full account of the dynamic response of the structure to a given earthquake was taken and maximum values of the stresses and deflections within the arch during the passage of the earthquake were produced.

TABLE 3 - Summary of Development Work on Arch Dams

Dam	Organization	Analysis - Method of Development	Background and Capability	Model Analysis			
				Material	Scale	No. of Models	Study of
Stithians Dam	I.C.	3D - Dynamic Relaxation	H, S G, H, S	Araldite Micro-concrete	1/100 1/60	1 1	E E, F, UE
Monar Dam	I.C.	3D - Dynamic Relaxation	S, H	Cement mortar	1/60	2	E, SP, F
Hendrick Verwoerd Dam	I.C. I.C., R.A.E., B.U.	3D - Finite Element 3D - Finite Element	G, H, S D	 Micro-concrete	1/100 1/200	1 1	Static and overall behaviour SS
Dam Type 1	B.U. U.N., R.C., L.C.T.	3D - Dynamic Relaxation Photoelastic method	H, S H, S	Rubber Thermo setting resin	1/50	1	Displacements SP
Dam Types 2, 5	U.N., R.C., L.C.T.	Photoelastic method	H, S	Thermo setting resin			SP
Dam Type 3	U.N., R.C., L.C.T. I.C.	Photoelastic method 3D - Dynamic Relaxation	H, Different Valleys G, H, RV, S	Thermo setting resin Cement mortar		 1	SP E, F
Dam Type 4	U.N., R.C., L.C.T. B.U. I.C.	Photoelastic method 3D - Dynamic Relaxation 3D - Dynamic Relaxation	H, S H, S H, RV, S	Thermo setting resin Rubber Cement mortar	 1/4	 1 2	SP Displacements E, F
Gravity Dam	I.C.	2D - Photoelastic method	G, H, S	Aluminium Alloy Thermo setting resin	1/400	1	E, SP
General	U.W. I.C. B.U. R.P.T.	3D - Finite Elements 3D - Finite Elements Finite Elements 3D - Dynamic Relaxation	T, AF, H, S, G EP, AD, SW, S, G, T G, H, S, D D, VF				

Capabilities of System

AD = Influence of Abutment Displacement
AF = Arbitrary Foundation
D = Dynamic Analysis
EP = Elasto-plastic Problem
G = Gravity Load
H = Hydrostatic Load
RV = Rigid Valley
S = Static Analysis
SW = Effect of Self Weight
T = Temperature
VF = Variable Valley Flexibility

Model Studies

E = Elastic Response
F = To Failure
SP = Stress Pattern
SS = Seismic Sensitivity
UE = Uplift Effects

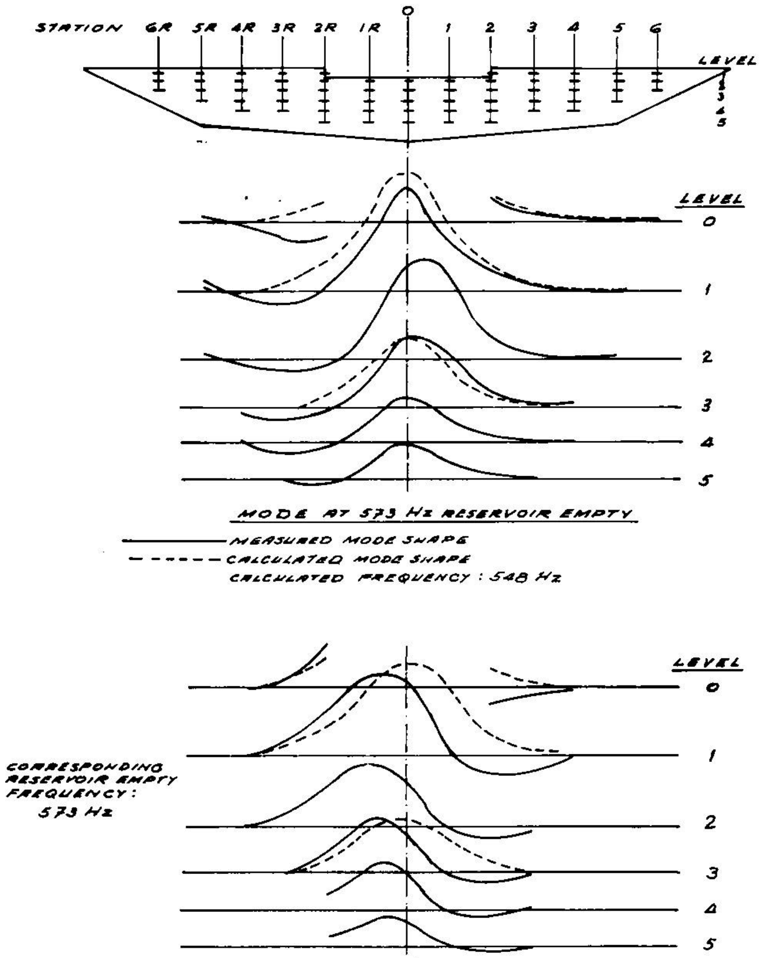
Organizations

I.C. = Imperial College, London
R.A.E. = Royal Aircraft Establishment
B.U. = Bristol University
U.N. = University of Nottingham
R.C. = Richard Costain Limited
L.C.T. = Lanchester College of Technology, Coventry
U.W. = University of Wales
R.P.T. = Rendel, Palmer & Tritton & Partners

FIG. 12

SEISMIC INVESTIGATION ON THE HENDRIK VERWOERD ARCH DAM (BACK et al)

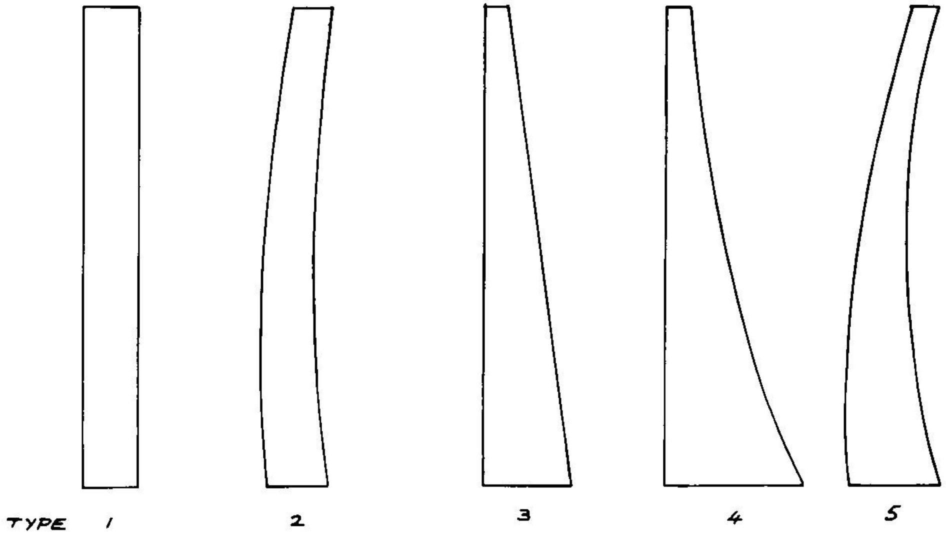
FUNDAMENTAL SYMMETRIC MODES: RESERVOIR EMPTY AND FULL.



MODE AT 434 Hz RESERVOIR FULL

MEASURED MODE SHAPE

CALCULATED MODE SHAPE ON FREQUENCY: 488 Hz



CROWN CROSS-SECTIONS OF ARCH DAM MODELS SELECTED FOR STUDY BY THE BRITISH COMMITTEE ON ARCH DAMS (1958-1968)

FIG. 11

The work was supplemented by a micro-concrete model to a scale of 1 : 200 which was built at Imperial College with a valley block large enough to give adequate flexural restraint to the dam. Fig. 12 shows the calculated and measured distortions; these are not strictly comparable because no allowance has been made in the calculations for curvature of the face of the dam in a vertical direction.

Recently, attempts have been made to overcome the non-applicability of standard seismic data to a specific location by recording in the area of the dam micro-seismic activities(40). This approach may be limited due to the problems of extrapolation of such data to a full scale earthquake condition where the non-elastic behaviour of both the ground and the concrete may be dominant.

5.3. Field Instrumentation

In the U.K. there are at least 30 large concrete dams which have been instrumented and have provided records of performance over the last 20 years. Moffat(41) of the University of Newcastle is attempting to establish a record centre for instrumentation data for U.K. dams in order that comparison of long term behaviour of dams can be made. Further, it would enable guidance to be given on instrumentation in order to avoid common problems in the performance and analysis of dam instrumentation. The important field of structural deterioration as regards safety, would also be included in this work. This latter aspect is one which the designer/analyst may tend not to consider.

A recent comprehensive investigation into the performance of the Clywedog Buttress dam in Wales was undertaken for the Construction Industry Research and Information Association(42). Measurements were made of internal stress and strain together with external deflection of the dam and measurement of seepage and uplift pressures in the dam foundation. A simple method of using basic creep data measured separately was developed to deduce stress from strain readings.

6. CONCRETE TUNNEL LININGS

6.1. General

Although a considerable amount of experience has been gained in the design and construction of tunnels, the design of tunnel linings remains an art rather than a science, because of the inherent variability of the main design parameter - the ground. It is not possible to set down a definite list of design rules nor has a code of practice to meet any contingency been produced. It is a rare event if a projected tunnel and it surrounding ground is exactly similar to a previously completed tunnel. Extrapolation of the basic parameters of previous work is only really applicable in the case of tunnels of similar diameters , wall and known ground conditions. Further, it is only the large capital projects such as the Channel Tunnel where meaningful savings can be achieved by refinements in design methods(43)

Currently, global factors of safety of up to 4 times the design loading are used except for major projects where extensive information on ground conditions can reduce the factor to more realistic levels.

6.2. Design Problems

In designing a tunnel lining the stiffness of the lining has to be related to the characteristics of the ground since the strength of the lining is related to both factors. Since the characteristics of the ground before and after instrumentation of the tunnel are usually different, the behaviour of both are considered. The geological conditions of the ground are difficult to predict and no satisfactory method is as yet available. Further judgement related to tunnelling experience is needed to estimate ground loads since full depth loading may not always occur.

6.3. Methods of Design and Analysis

Many tunnel designs have been based on empirical methods which involve simple proportioning of the parameters of the lining to that of previous designs or by the use of a simplified approach(44). However, analytical methods of designing tunnel linings are available which can cope with most design requirements. Finite element techniques, for example, have been developed for the numerical analysis of a large number of boundary conditions, mostly in two dimensions and occasionally in three. The practical usefulness of these methods has been restricted by the uncertainties as to the ground conditions, e.g. degree of fissuring, water flow, the non-isotropic elastic/plastic material properties, and also the variation in ground conditions along the length of the tunnel. Further non-uniform loading can arise during erection.

To overcome the non-uniform loading of unreinfoced precast concrete linings, a lining composed of flexible cross joints (Fig.13a) has been used in London clay for the Victoria Underground line(45) and currently in the Fleet line(46) under construction. Reduction in bending movements resulted in a better distribution in stress and increase in strength. Fig. 13b also shows the effect of joint rotation on the ultimate strength of the joint. Multiaxial self-restraint was considered to be responsible for the high load achieved. The same concept is being considered for use in the Channel Tunnel.

6.4. Field Instrumentation

In the last few years some effort has been devoted to the instrumentation of actual full scale tunnelling situations, particularly by the Building Research Establishment and the Transport and Road Research Laboratory. In situ measurements, for example, were carried out in the Cargo tunnel at Heathrow Airport, London(47), Victoria Underground line(45) and currently for the Fleet line of the London Underground(46).

In the case of the Victoria line(45), results showed that after six years, the horizontal diametral deformation of a 4 m dia. experimental length of tunnel had increased by as much as 10 mm, showing the continuing change of state in the surrounding clay.

In the case of fissured rock, load, pressure and hoop measurements were made on the bolted concrete lining with grouting for the Severn and Wye cable tunnel(48). As shown in Fig. 14, the results demonstrated a non-uniform loading of the lining and a redistribution of stress with time, showing stability had not been reached within the 7 month period of measurement.

Considerable data in designing reinforced concrete linings in rock environments will be gained from the in situ measurements to be carried out during the preliminary driving for the Channel Tunnel at present under construction.

7. OTHER AREAS OF ACTIVITY

7.1. Triaxial Stresses in Construction

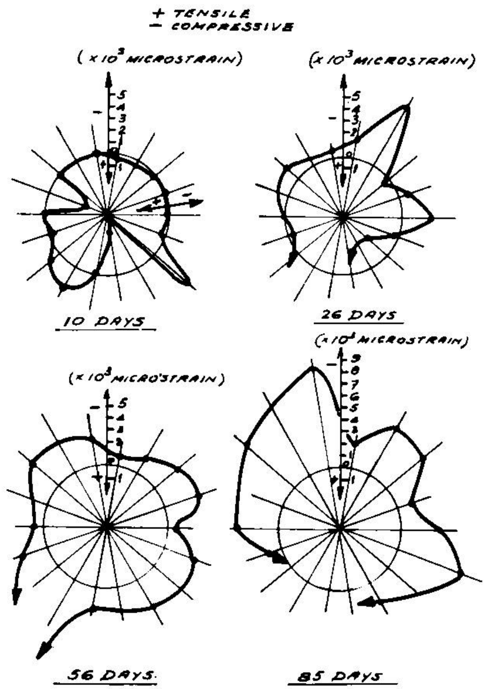
In the construction of mass concrete structures whether dams, pressure vessels or concrete foundations for buildings, uncertainty has prevailed for many years as to the effect of size and temperature rise from cement hydration on cracking and joint movement.

Work by Hughes of Birmingham University(49) resulted in a method of designing the steel reinforcement requirements to control cracking from thermal contraction strains.

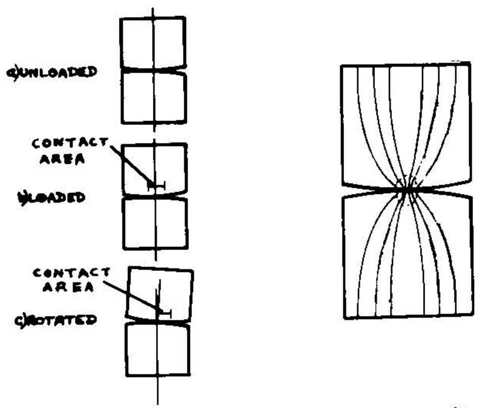
TUNNELS IN FISSURED ROCK:

MEASURED HOOP STRAIN IN BOLTED RING SEGMENTS AFTER GROUTING.

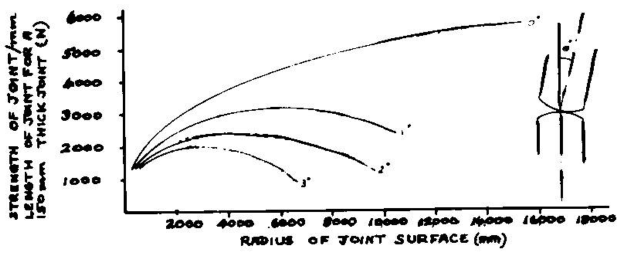
SITE: TUNNEL UNDER SEVERN – WYE ESTUARIES.
INTERNAL DIA. = 3 metres.
(HASWELL)



EXPANDED FLEXIBLE PRECAST CONCRETE TUNNEL LINING IN THE VICTORIA LINE (MORGAN AND BARTLETT).



LEFT – DETAILS OF CROSS JOINTS IN CONCRETE LINING.
RIGHT – FLOW LINES OF LONGITUDINAL STRESS.



RELATIONSHIPS BETWEEN STRENGTH OF JOINT AND RADIUS OF SU FACES FOR V. DEGREES OF JOINT ROTATION.

Instrumentation of 200 m^3 pours in pressure vessel construction and form foundation structures together with experimental work at the authors laboratories (50) have demonstrated the degree of restraint that can build up (Fig. 15) and the stresses that are locked into a pour as a result of the heating and cooling cycle that takes place over the first 2 - 3 weeks after placing. Such locked-in stresses, besides being of interest in relation to cracking and joint movement, are not considered at all at present in subsequent design or analysis considerations. The above work has also included the influence of concrete additives and cement types as well as lift height and bay length on the temperature rise and its effects.

7.2. Buildings and Piled Foundations

In the design of piled rafts for buildings in London clay, Hooper(51) has reported on a finite element analysis undertaken on the foundation of 90 m tower block on London clay in which load cells were installed. Good correlation between the theoretical loads and displacements after six years was found. Field results showed that the load distribution between the piles and the raft for the completed structure was in the region of 6 : 4 and that the foundation stiffness was 10 times greater than the raft itself due to rigidity of the substructure, the contribution of the superstructure being relatively small.

Perhaps in the near future more attention will be given to the global interaction of the building with dead and live loads and the way load is transmitted to the ground.

7.3. Offshore Structures

With the discovery of the North Sea Oil, there is a rapidly increasing demand for offshore concrete gravity-type structures to be used for oil production and/or for oil storage. These structures are massive and although the geometry may be simple they require careful design to cater for stability, wave forces and sea bed conditions.

Their unique feature is they consist of a number of massive components, e.g. raft, pods and towers, which are interlinked (Fig. 16). Individual components demand a sophisticated and lengthy type of analysis. Computer programmes using finite elements and grillage types of analysis are being used. These design tools are capable of describing the behaviour of each component and the interaction between them. Further development work into the application of these methods is in progress.

The combined action of the various components and the partial passive restraint which is provided by the continuity of the structure, create triaxial states of stress. This no doubt will enhance the limit of cracking and the ultimate strength. It has been established that lateral restraint, especially in slabs(52 & 53) increases considerably their flexural and shear strength due to the increase in the compressive membrane forces. Advantage might be taken of the triaxial state of stress in many parts of such structures and hence increases in the allowable stresses may be possible.

FIG. 15.

DEGREE OF RESTRAINT TO FREE THERMAL MOVEMENT DURING THE HEAT OF HYDRATION THERMAL CYCLE IN A MASS POUR (BROWNE & BLUNDELL)

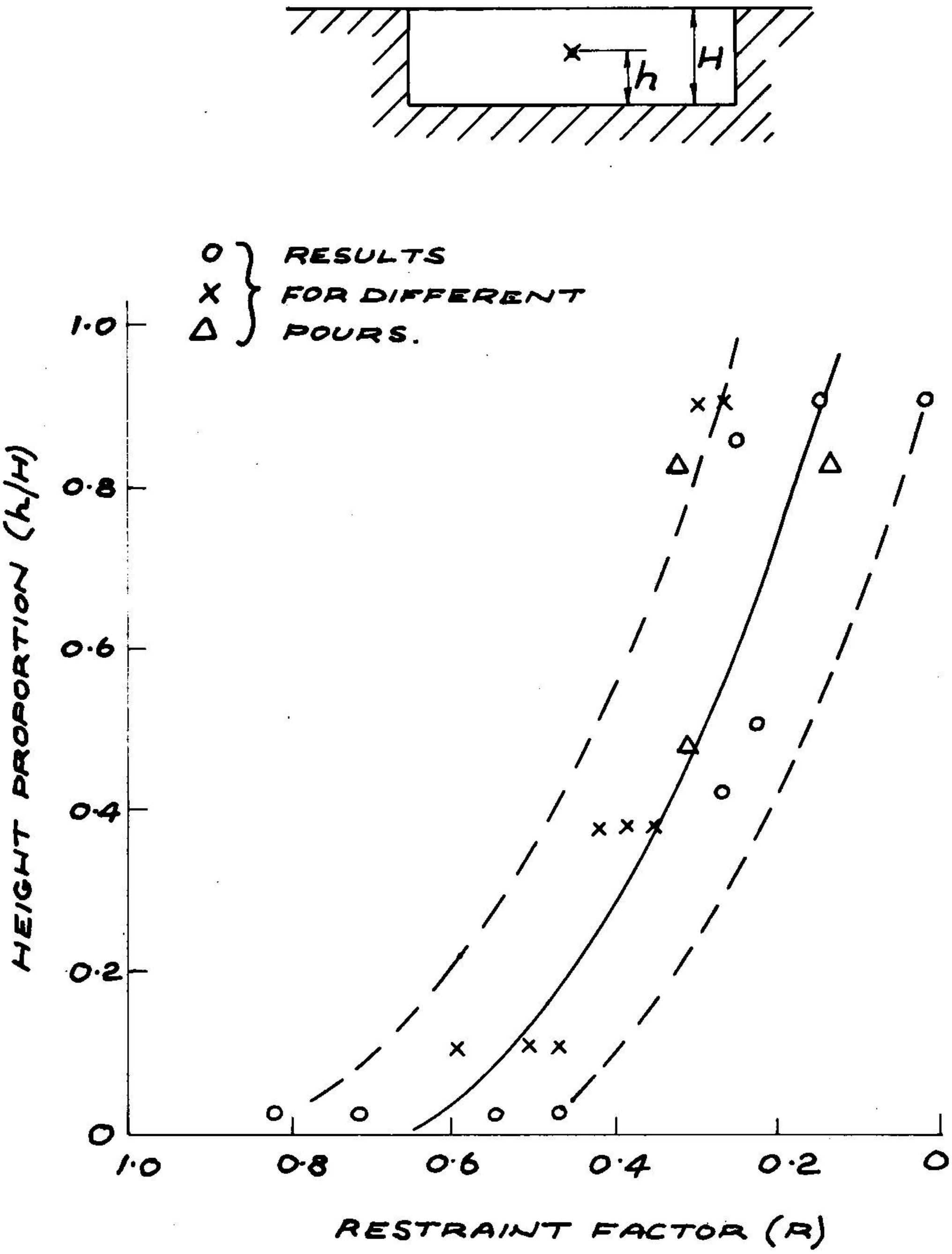
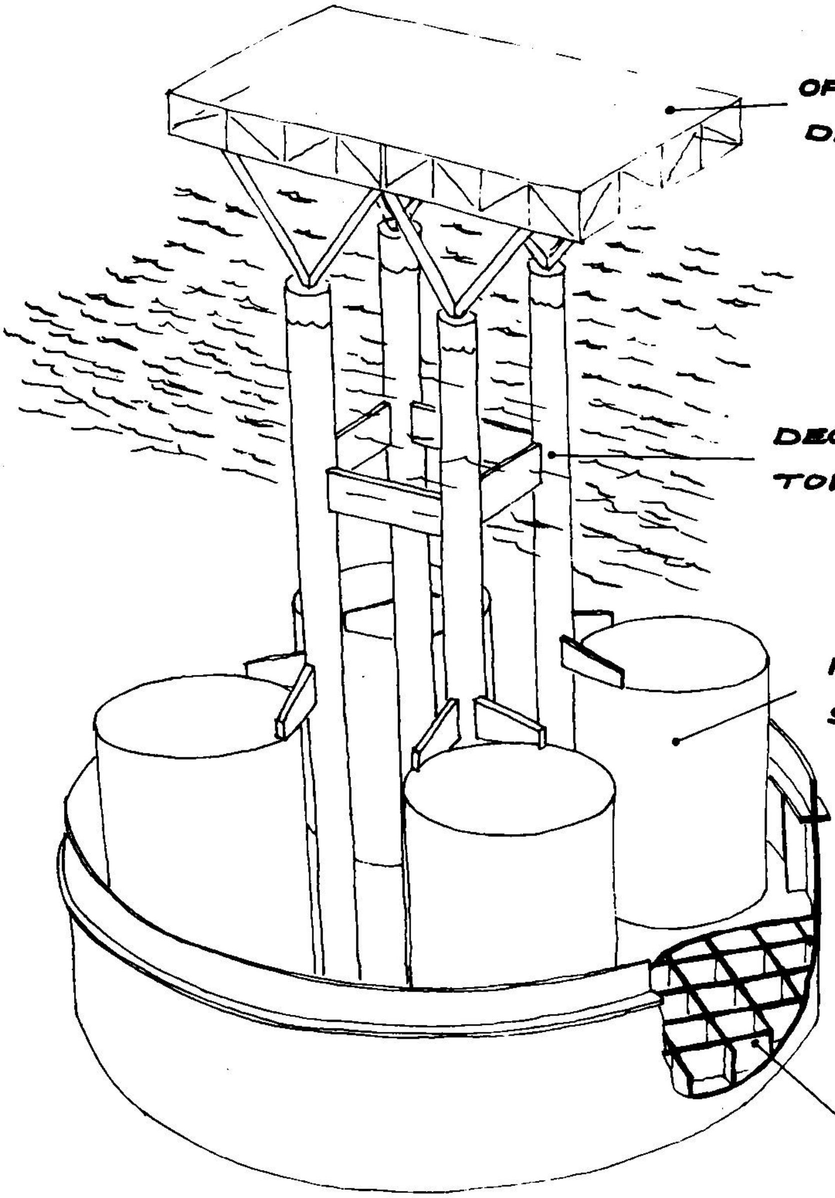


FIG. 16

OFF-SHORE DRILLING RIG

CONCRETE GRAVITY STRUCTURE



8. CONCLUSIONS

8.1. In the U.K., research and development is active on all fronts and in particular, the demands on understanding the detailed behaviour of concrete pressure vessel for the nuclear power station programme has stimulated considerable advances both in universities, government and commercial establishments.

8.2. Development of analysis and design methods, to handle overload and time dependant states as well as variable natural boundary conditions, are being supported by model analysis and to a somewhat lesser degree, by feed-back from field instrumentation.

8.3. So far, the design standards and codes of practice[54] have only to a limited degree provided guidance on the many factors outlined in the paper involved in the design of 3-D stressed structures but they have left the way open for progress in this field. In certain applications, such as dams and tunnels, uncertainties in environmental loadings etc. have prevented the preparation of such documents since design depends so much on specialised experience in the field.

8.4. The benefits of higher strength achieved under triaxial compressive states have been so far only utilised in small component applications where the applied stress states can be controlled to a close degree.

8.5. Finally, the authors believe that this Seminar will provide a valuable link to all those engineers involved in widely different applications of concrete in triaxially stressed states since cross-fertilisation of techniques of design, analysis, material and model behaviour combined with field measurements could well stimulate progress.

Recommendation

To ensure that future progress is broad based in the total 'matrix' area defined in the Introduction to this Report, it is suggested that the IABSE or some other appropriate international body should, if possible,

(i) set up a reference bank for data on all aspects of this important subject

(ii) arrange that an analysis of data in each component field is produced in a form directly usable to the designer.

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SUMMARY

The paper first summarises the parameters that should be considered in assessing progress in the areas of materials research, theoretical and model analysis, design and field observation relevant to triaxially stressed concrete applications. The main part of the paper consists of a survey of Research and Development in the United Kingdom on structures which could utilise triaxially stressed material properties. The application to nuclear pressure vessels is discussed in detail . Reference is also made to other types of structures, such as dams and tunnels, highlighting the major design problems in relation to the stress states.

RESUME

Le rapport traite d' abord les paramètres qu' on doit considérer pour obtenir des progrès dans les domaines de la recherche sur matériaux, de la analyse théorique et par maquettes, du projet et de la réalisation, en relation aux applications du béton sous contrainte triaxiale. La partie principale du rapport représente un panorama des recherches et des développements dans le Royaume-Uni, sur structures qui pourraient utiliser les propriétés des matériaux chargés triaxialement. On discute en détail l' application aux caissons en pression pour réacteurs nucléaires. On fait aussi référence à d' autres types de structures, comme barrages et tunnels, en soulignant les problèmes plus importants du projet, en relation aux états de contrainte.

ZUSAMMENFASSUNG

Der Artikel fasst zuerst die Parameter zusammen, die zur Erzielung von Fortschritten auf den Gebieten der Werkstoff-forschung, theoretischen und Modell-Analysen, Beobachtungen bei Design und Ausführung von dreiachsigen Spannbeton-Konstruktionen zu berücksichtigen sind. Der Hauptteil des Artikels bietet einen Überblick über Forschung und Entwicklung in Grossbritanien hinsichtlich solcher Konstruktionen, für die die Eigenschaften von dreiachsigen Werkstoffen von Nutzen wären. Auf die Verwendung für Spannbeton-Druckbehälter wird ausführlich eingegangen. . Auch andere Typen von Konstruktionen, wie Deiche und Tunnels, werden erwähnt, wobei die hauptsächlichen Design-Probleme im Zusammenhang mit der Druckspannung hervorgehoben werden.