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Summary Report on Theme IV

Rapport sommaire au thème IV

Zusammenfassender Bericht zum Thema IV

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1. Comments on the Prepared Discussions

Seven contributions were made to the prepared discussion of this Theme.

Ohno, Shibata and Hattori present a review of the results of shear tests conducted on 378 reinforced concrete column specimens conducted in Japan since 1961. The tests allow an assessment of the shear strength and ultimate lateral deformability at the shear failure of columns with both monotonic and repeated reversed loading. A shear strength equation is obtained from the experimental data which shows the shear strength as a function of the axial load, shear span/depth ratio, size of specimen, concrete compressive strength, web and axial reinforcement contents and the yield stress of the steel. No noticeable difference between the strength under monotonic or repeated reversed loading is found. Equations for ultimate deformation due to shear are also given. The apparent absence of the effect of reversed loading on strength and deformability is a surprising result which may have been due to experimental scatter. This aspect requires further investigation.

Celebi and Penzien present test results from beams with column stubs tested under reversed loading and show that a marked pinching of the load-deflection loops occurrs when the shear force is high, leading to a deterioration of stiffness due to shear. In their test beams when the nominal shear stress $V/bd = 3.75\sqrt{f'_c}$ psi the pinching is very significant but at lower nominal shear stress the effect of shear is not noticeable. Thus it is important to include the possible influence of shear in models for reversed load-deflection behaviour and these test results are of assistance for such modelling. A comparison of dynamic and static loading results from their tests also shows an increase in the initial yield for dynamic loading but no significant difference between subsequent static and dynamic load-deflection loops. This is a welcome result because it does mean that load-deflection

(* In the absence of Prof. V.V. Bertero who was unable to attend the Lisbon symposium due to illness) loops obtained from static loading tests can be used with more confidence in dynamic loading situations.

Morita and Kaku produce experimental evidence for the local bond stress-slip relationship under repeated loading found from tests on short concrete elements. Empirical equations are given which fit their test results well. The results are a useful addition to available information on the deterioration of bond with repeated loading.

White and Chowdhury present results from tests performed on 1/10 scale reinforced concrete beam-column assemblies which show very good load-deflection and moment-rotation agreement with prototype tests conducted by the Portland Cement Association. They also present results obtained from 1/10 scale three storey two bay reinforced concrete frames subjected to vertical loads plus reversing horizontal loads. The monotonic load-deflection curve was the envelope for the cyclic loading curves. The paper concludes that well detailed frames do not deteriorate significantly under severe cyclic loading and that small scale models may be used to investigate reversing load phenomena in reinforced concrete. The importance of meeting model material similitude requirements, for example concrete tensile strength, as closely as possible is emphasized. A point of interest is that the stiffness of the model frame under reversed lateral loading reduced very considerably (for example, to about $\frac{1}{3}$ of the initial stiffness), presumably due to softening of plastic hinges and bond deterioration. Such stiffness degradation will have a considerable effect on the response of a structure to dynamic motions.

Yamada, Kawamura and Kondoh report results from cyclic load tests conducted on reinforced concrete rectangular frames in which plastic hinging formed in either the beams or the columns. The theoretical load-deflection behaviour is computed using idealized stress-strain curves for the steel and concrete and reasonable agreement with the test results obtained. The effect of vertical load level on behaviour, particularly the softening of stiffness, is illustrated.

Tichý and Urban present experimental evidence which tends to show that for prestressed concrete beams which fail in compression, where an increase in the steel stress is possible, repeated loading may cause an increase in the load carrying capacity. They postulate that this is due to repeated loading causing a separation of the tension and compression zone of the member due to cracking and that the deformation of the concrete then becomes no longer dependent on the deformation of the steel. Thus a greater concrete force may be available and result in an increase in the ultimate moment capacity. However, on average the percentage increase is small, generally much less than 10%.

Muguruma, Tominaga, Takaya and Tada present test results for the flexural behaviour of prestressed concrete beams under repeated reversed loading. An idealized moment-curvature curve for prestressed concrete flexural members is proposed which takes into account deterioration of strength and stiffness with loading cycles. Compression steel and stirrups are shown to improve the ductility. This paper gives useful information regarding the shape of moment-curvature hysteresis loops for a number of variables which could be used in realistic dynamic analyses of prestressed concrete structures.

2. Concluding Remarks

2.1 Experimental Studies

Professor Bertero's comprehensive introductory report has been complemented by the contributions to the prepared discussion. Some general conclusions which may be drawn are as follows.

Reinforced Concrete

For reinforced concrete members (elements) when flexure dominates (low shear), properly detailed members can develop very high inelastic deformations. The flexural stiffness reduces with each cycle of loading but the maximum moment capacity does not reduce unless crushing of the concrete causes a reduction in the concrete cross section. Final failure may be due to buckling of compression steel. When flexure occurs with a high shear force, say a nominal shear stress V/bd greater than $3\sqrt{f'_c}$ bd psi, an additional reduction in stiffness may occur in each cycle of loading due to shear, and failure may be initiated by shear. Web reinforcement should be provided to carry the greater part of the shear force. When flexure occurs with high shear and high axial compressive force, the reduction in the strength and stiffness with each cycle of loading may be substantial unless the column contains adequate transverse steel for shear reinforcement and concrete confinement. Hence there may be a substantial reduction in ductility unless columns contain closely spaced steel hoops.

A better indication of the behaviour of reinforced concrete members in frames may be obtained by testing beam-column assemblies. When lateral loading is applied to a frame substantial shear and bond forces need to be carried across the panel zones of beam-column joints. For example, a beam reinforcement bar passing through a column will be in compression on one side of the joint core and in tension on the other side, and hence twice the yield force of the bar may need to be developed by bond in the panel zone. Also, the horizontal shear force to be carried by the panel zone is twice the tensile force in the beam. Tests have shown that shear reinforcement is required in the panel zone of joints to prevent failure under cyclic load conditions which simulate reversed lateral loading on structures. If the beams frame into the columns on all four sides, the panel zone may be well confined by the surrounding beams and the problem may not be so serious. However if a single beam frames into only one or two sides of a column it may be difficult to prevent a shear failure occurring in the panel zone even with large quantities of shear reinforcement present. This is due to alternating diagonal tension cracks, which open and close in the panel zone as the direction of loading alternates. These cracks may eventually cause the concrete in the panel zone to break up, leading to a loss of strength and stiffness of the joint core.

Shear walls provide an effective way of carrying lateral forces in buildings and because of their greater stiffness they generally provide superior protection against damage. It is a wide spread belief that shear walls are brittle. Recent studies show however, that properly detailed shear walls can be ductile enough to sustain large lateral loads repeatedly while undergoing plastic deformations comparable with those expected in framed buildings.

Prestressed Concrete

Tests have shown that large post-elastic deformations can be obtained from prestressed concrete flexural members providing steel contents are not excessive. Energy dissipation prior to crushing of the concrete is small but is substantial once crushing of concrete has occurred. A reduction in stiffness occurs with high intensity cyclic loading. Mortar joints between precast post-tensioned frame members can behave satisfactorily under high intensity load reversals.

2.2 Future Research

Areas where future cyclic loading experimental research is still required involve the buckling of compressed reinforcing steel, shear-axial load-flexure interaction, beam-column and slab-column joints, shear walls, rate of strain effects, repair of members after damage, and the behaviour of complete structures.

Also, the full theoretical moment-curvature curve may require too much computer time for practical frame analysis and simple idealized curves may be adequate for use in the non-linear dynamic analysis of structures responding to earthquake motions or to wind. Simple idealizations already exist, for example, Clough's degrading stiffness model for reinforced concrete. More research is required to determine more accurate idealized moment-curvature loops and idealized deformation characteristics due to bond slip in plastic hinge regions and due to shear at plastic hinge regions and in panel zones of joints. This has already been discussed with regard to Theme I.

Experimental studies of reinforced subassemblages should also give an indication of the ductility requirements at critical plastic hinge regions in order to achieve the deflections required when structures respond non-linearly to earthquake motions, so that designers can detail sections for adequate rotation ductility. It is to be noted that the displacement response of a structure to a severe earthquake will depend on the shape of the load-displacement loops and hence, for example, prestressed and reinforced concrete structures will have different ductility demands.

In general the loading direction of earthquakes will cause biaxial bending and shear of columns and joint cores because the loading will seldom act in the direction of a principal axis of a building. Thus the shear strength of diagonally loaded columns and joint cores should also be considered. At present there is very little experimental evidence of the shear strength of members with diagonal loading.

The question of the repair of structures is a very important issue. More research is needed to determine whether badly damaged members can be repaired satisfactorily. Cracked members can be repaired by injecting epoxy resins into cracks as has been found at Berkeley University, and some badly crushed members have been repaired by replacing the damaged concrete by new concrete at the University of Canterbury. However more tests will be necessary before such repairs can be recommended with confidence.

Finally it is important that future testing should be carried out on realistic specimens involving subassemblages of beams, slabs, columns and walls where necessary to include all interaction effects.

SUMMARY

The contributions to the prepared discussion of Theme IV: Experimental Studies Concerning Reinforced, Prestressed and Partially Prestressed Concrete Structures and their Elements are commented upon briefly. Concluding remarks on experimental studies are made and areas requiring further research are indicated.

RESUME

Les contributions à la discussion préparée concernant thème IV sont brièvement commentées. On donne des remarques de conclusion sur des études expérimentales et on mentionne les domaines où des recherches ultérieures sont indiquées.

ZUSAMMENFASSUNG

Die Beiträge zur vorbereiteten Diskussion betreffend Thema IV werden kurz kommentiert. Es werden Schlussbemerkungen über experimentelle Studien angebracht und Gebiete bezeichnet, die weiterer Forschung bedürfen.

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