IMPROVED STRENGTH AND DUCTILITY IN CONCRETE ELEMENTS FOR EARTHQUAKE RESISTANCE

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ABSTRACT

This paper describes tests on a novel method of confinement in which high tensile steel bolts were inserted horizontally in two orthogonal directions, through pre-formed ducts, in small concrete prisms. The prisms were then loaded concentrically in the third direction. In half of the specimens, the bolts were pre-tensioned; additionally, in two specimens, the annular space between ducts and bolts was grouted. Load was applied monotonically to maximum load, and in some prisms, loading was continued well after maximum load was reached. Very significant enhancement of load-carrying ability and ductility of the concrete was obtained. Strength gain over plain concrete prisms was up to 100%, while mean longitudinal strains of between 50,000 and 100,000 microstrains were attained. Specimens displayed a great energy absorption capacity during testing to maximum load. Indications are that the absorbed energy was largely dissipated in the permanent deformation of the specimens; possible applications to earthquake resistant structures are discussed.

INTRODUCTION

It is well known that both high strength and ductility are desirable in concrete structures designed to withstand seismic loading. In critical zones such as hinges and other high compression zones, also in beam-column joints, the provision of suitable reinforcement is crucial for two reasons; firstly to ensure adequate reserves of strength to resist overstressing resulting from earthquake movements, and secondly, to provide sufficient ductility to dissipate the energy from such vibrations. Although this may be achieved by placing well-anchored reinforcement across principal tensile zones, appropriate confinement of concrete in two or three directions also produces enhanced strength and ductility (1,2). In both cases, prestressing of the tensile and confinement steel can further improve structural performance. The benefits of prestressing are not usually exploited in critical zones requiring short lengths of tensile reinforcement nor in lateral confining reinforcement except, occasionally, in prestressed spirals in columns. Nor are the benefits of lateral confinement much exploited, other than in compression regions where spirals and rectilinear stirrups can be suitably placed.

This paper describes exploratory work undertaken in the Civil Engineering Department, Imperial College on the use of short 'linear' steel reinforcement to introduce passive or active lateral confinement in small concrete prisms, and thus enhance both load-carrying capacity and ductility.

METHOD OF CONFINEMENT

Confinement in the concrete prisms was provided by high tensile steel bolts inserted horizontally in two orthogonal directions (Fig. 1). The prisms were loaded in the third (longitudinal) direction, and the resulting lateral expansion of the concrete was resisted by an increasing tension in the bolts. While the action of the bolts was comparable to that of rectangular links or spirals, the resulting confining forces were more discretely applied, and mild steel washers were used to distribute these concentrated forces. Fig. 1 also shows the cage of steel mesh placed in each prism near the concrete surface to help in lateral load distribution and to offer secondary confinement. The beneficial effects of lateral prestress have been reported in studies of spiral reinforcement (3); to this end, an initial bolt tension was applied to some of the test specimens.

The work being exploratory in nature, attention was concentrated on the general strength and deformational characteristics of the bolt-reinforced prisms, and the nature and effectiveness of this method of confinement.

DETAILS OF TEST SPECIMENS

All specimens were 138mm x 138mm x 414mm rectangular prisms. A rectangular arrangement of ducts was cast in each specimen to accommodate the 54 bolts. Ducts were formed by steel rods sheathed with pvc tubing. These rods were inserted prior to casting through a grid of holes drilled through each side of the moulds, and were removed once the concrete had hardened. The steel bolts were 150mm long and 7.8mm in diameter, with an ultimate load capacity of 34.6kN. The mild steel washers were 2.05mm thick, with internal and external diameters of 9.82mm and 22.30mm respectively. Mild steel mesh of 1.625mm diameter and 12.5mm square pitch was used to fabricate the cages.

The tests reported here were concerned mainly with prisms in which the annular space between each duct and bolt was left ungrouted. However, two prisms were grouted with epoxy resin one week before testing.
A method was devised to inject grout into the annular space through a small duct in the head of each bolt. The bolts in one of the two specimens were pre-tensioned before grout was injected.

Altogether five specimens had bolts pre-tensioned before testing. Bolts were stressed to about 220 N/mm^2 (equivalent to an average lateral stress on the concrete of 4.96 N/mm^2) by means of a torque wrench. Except for the grouted specimen, tensioning was carried out on the day of testing.

A mix with a characteristic strength of 50 N/mm^2 , maximum aggregate size of 10mm. and water-cement ratio of 0.58 was used throughout. Specimens were cured in water for 7 days and stored in the laboratory until testing. Plain concrete control prisms of similar dimensions, and 4-inch cubes were also cast and match-cured. Details of the specimens tested are summarised in Table 1.

TESTING PROCEDURE AND INSTRUMENTATION

Specimens were concentrically loaded in an Amsler testing machine at a longitudinal strain rate of approximately 7 microstrains ($\mu\varepsilon$)/second. All specimens were loaded monotonically to maximum load; additionally, for two untensioned and two tensioned prisms, loading was continued well after maximum load was reached.

Two sets of longitudinal displacements were recorded: between-platens displacements by 4 LVDTs (linear voltage displacement transducers) one on each side of the prisms, and displacements over the central third section of the prism by 4 similarly positioned LVDTs mounted between two compressometer frames (Fig. 2). The axial strain in one mid-face bolt at the cross-section between the compressometer frames was measured by a pair of electrical resistance strain gauges, and converted to the equivalent bolt confining force on the concrete.

DESCRIPTION OF EXPERIMENTAL BEHAVIOUR

Ungrouted specimens. The appearance of vertical cracks was the first sign of distress. Thereafter, the rate of increase in load dropped steadily. The stress at which cracking was first observed in untensioned prisms was smaller than that for the plain concrete prisms (f'_{cr}) whilst the corresponding value for tensioned prisms was slightly greater than f'_{cr} . As loading continued beyond the plain concrete strength (f'_u), surface spalling led to a progressive reduction of the area of intact core of confined concrete. Spalling first occurred at the levels containing orthogonal sets of bolts (region A in Fig. 1) but later spread to other regions, and was finally most severe in the regions of concrete furthest from the confining bolts (region B). Concrete immediately around the bolts remained intact. Confinement provided by the mesh gradually diminished as it bent outwards and buckled locally under the higher loads.

A prominent feature of behaviour was the large rate at which strain increased with load at loads close to the maximum. Corresponding strains in the tensioned specimens were always less than those in the untensioned types. Although load capacity was maintained at unusually large strains, there was evidence of extensive shape and material deformation during advanced stages of loading. This took the form of severe spalling, local crushing, deformation and local buckling of mesh cages, bending of the bolts, dishing of some washers, visible bending of the prism and increasing differences among the four middle third displacement readings. Some of these features can be seen in Fig. 3. The figure also clearly shows the extent of axial shortening which was almost totally permanent. Specimens loaded beyond maximum load displayed a remarkable capacity to withstand high loads despite large strains. Mean strains of more than 100,000 $\mu\epsilon$ were recorded at loads sustained at not less than 90% of the maximum (Fig. 6).

Grouted specimens. As anticipated, the behaviour of grouted and ungrouted prisms showed significant differences; in the former, load increased steadily to maximum without the same massive strains. Nevertheless, strains at maximum load were substantial and values ranging from 15,000 to 20,000 $\mu\epsilon$ were recorded. Similar visible features of deformation were present but these were less pronounced. Early spalling tended to occur more uniformly over the prism surface; but, at higher loads, regions B again were most severely affected. Beyond the maximum, load fell off steadily.

TEST RESULTS AND DISCUSSION

The experimental results were used to obtain, for each specimen, the relationships between longitudinal stress and longitudinal strains measured over the middle third (ϵ_1) and the entire height (ϵ_2) of the specimen; also, between longitudinal concrete stress and stress in the steel bolt. Fig. 4 and 5 show typical results for each group of similar specimens. Longitudinal stress values were based on the gross concrete cross-sectional area. In Fig. 5, curves for the tensioned specimens have been offset to the left by the amount of pre-tension in the bolts. Fig. 6 shows the longitudinal stress-strain curves for two of the specimens tested beyond maximum load. Stress-strain curves at low loads are compared for the various prism types in Fig. 7. Finally, the main results are summarised in Table 1. From an examination of Table 1 and Fig. 4, 6 and 7, the following observations can be made:

a. Three distinct groups of specimen behaviour can be identified namely, (1) plain concrete prisms, (2) ungrouted and bolted prisms, and (3) grouted and bolted prisms.

b. The orthogonal arrangement of bolts produced considerable strength increase, up to twice f'_u in grouted prisms.

c. Ungrouted specimens were extremely ductile; the corresponding strains in grouted specimens were small in comparison but were still substantial at maximum load. On complete unloading, no specimen showed any significant elastic recovery (Fig. 6).

d. After reaching maximum load, the ungrouted specimens exhibited only a small degree of strain-softening up to extreme values of 100,000 $\mu\epsilon$ or more.

e. From early stages of loading, ungrouted prisms had a low stiffness of about 17 kN/mm². This deteriorated rapidly after the onset of cracking. The corresponding stiffness of grouted prisms (about 26 kN/mm²) on the other hand was more comparable to that of plain prisms (about 30 kN/mm²) but reduced steadily after f'_u was reached. In both cases, stiffness was improved by the presence of an initial tension in the bolts.

Action of bolt reinforcement. Fig. 5 shows that up to longitudinal stresses approaching f'_u , bolt stresses were low due to the small lateral concrete expansion. Beyond this, they increased more quickly as bolt tension was mobilised by large lateral concrete strains. Bolt stress started to increase rapidly at lower loads in ungrouted specimens than in grouted ones; this is attributed to the weakening effect of the annular duct space.

The distribution of confinement stresses in each prism was highly non-uniform; as a result, certain regions of the surface (B in Fig. 1) received least confinement and suffered the most severe damage at high loads. Examination of specimens after test revealed that the effective core still extended to the prism surfaces at the positions of the bolts. At high loads, though the concrete was cracked and crushed badly, the bolts were able to hold the material together with little loss of load capacity.

Action of mesh. The mesh helped to distribute the concentrated confining forces in the immediate vicinity of the bolts. More importantly, as test observations suggested, the bolts restrained the lateral expansion of the mesh, which in turn, inhibited lateral concrete expansion. This effect was most significant in regions B where the direct influence of bolt forces was least.

Effect of initial tension. Tensioned bolts created a biaxial precompression in the concrete; a significant triaxial stress state developed soon after loading commenced. This improved both stiffness and the longitudinal stress at which the knee region in the curves of the tensioned specimens in Fig. 5 occurred. The stiffening effect was more evident in ungrouted prisms where it appeared that an initial confinement helped to offset the weakening influence of the ungrouted ducts. Only in the grouted prisms did pre-tensioning appear to produce significant improvement in strength.

Effect of grouting. The ungrouted ducts substantially reduced the effective concrete cross-sectional area, this explains both the massive strains in ungrouted prisms and their low early stiffness. Grouting improved stiffness throughout loading, and permitted significantly higher maximum stresses to be reached. Also, the corresponding strain of approximately 20,000 $\mu\epsilon$ was still significantly higher than typical strains observed in tests on prisms with rectangular links(4,5).

POSSIBLE APPLICATIONS

It is thus possible, by the method of reinforcement adopted, to produce significant increases in both strength and ductility. Moreover the large area under the stress-strain curves represents a huge energy absorption capacity. The severity of deformation and the negligible recovery of axial shortening on complete unloading showed that most of the energy so absorbed was dissipated. Despite their discrete nature, the bolts showed a remarkable ability to hold the highly distressed concrete together at high strains, thus ensuring a sustained load carrying capacity. Comparisons with typical stress-strain curves obtained for column units reinforced with spirals or rectangular links (3,4,5) suggest that the behaviour of grouted prisms lies between those of the two types of conventionally reinforced structures.

Some possibilities for application include hinge zones and regions of high local bearing stresses such as prestress anchorage zones and bridge bearing areas. In the latter case, the deployment of lateral prestressed reinforcement similar to that described here may be effective in preventing premature failure when the bearing zones are subjected to high lateral forces as in an earthquake. The type of lateral reinforcement need not be restricted to bolts - in large structures, prestressing wires can be used to provide the confinement.

Perhaps of more immediate application may be the use of bolt reinforcement in repairs, or in strengthening existing structures for seismic resistance. This may be in local zones of anticipated weakness in compression, for example, where basement columns of multi-storey buildings have failed as stub columns (due perhaps to unintentional interaction with solid infill panels), repair and strengthening with bolts might be an attractive alternative to demolition.

Finally, the successful use of the bolts suggests their application in internal beam-column joints. Many studies (6,7) have been conducted on the seismic performance of such joints, and it is clear that the degradation of joint stiffness and bond within the joint panel zone under seismic loads can lead to overall structural failures. In some structures, it may be possible to reinforce the panel zone additionally with bolts or prestressed bars in the manner shown in Fig. 8. Strictly speaking, this reinforcement is not providing lateral confinement in the manner tested, but its action in delaying or suppressing diagonal cracks in the panel zone may strengthen the joint and improve the bond anchorage of beam steel bars passing through the joint.

CONCLUSIONS

Results show that normal strength structural concrete confined by this method possesses increased energy absorption capacity with sustained load-carrying capacity; much of the absorbed energy was dissipated in permanent specimen deformation. These attributes are clearly of importance in the design of reinforced concrete structures for earthquake resistance. The work presented is part of a larger programme of tests at Imperial College on the response of structural elements under non-uniform lateral confinement. Investigations have also included varying the factors involved, such as mesh, washer size, and concrete strength(8). Further work will include a study of energy dissipation characteristics in detail.

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Table 1 Description of test specimens and mean results

No.	Specimen Type and Description	Age at Test	Cracking Stress* f_{cr} (N/mm²)	Maximum Stress* f_u (N/mm²)	Middle Third(ϵ_1) and overall(ϵ_2) strains at f_u*($\mu\epsilon$)		Values normalised with respect to plain concrete (f'_{cr} f'_u ϵ_1 ϵ_2)			
					ϵ_1	ϵ_2	f_{cr}/ (f'_{cr})	f_u/ (f'_u)	ϵ_1/ (ϵ'_1)	ϵ_2/ (ϵ'_2)
1-4	A: Bolted, with mesh	56 days	31 (42.5)	61.4 (43.0)	73495 (2100)	53165 (2285)	0.73	1.43	35.00	23.27
5-8	B: Bolted, tensioned, with mesh	56 days	44 (42.5)	65.7 (43.0)	58975 (2100)	46975 (2285)	1.04	1.53	28.08	20.56
9	C: Bolted, grouted, with mesh	16 mths	52 (46)	83.9 (51.0)	19595 (2490)	14815 (2590)	1.13	1.65	7.87	5.72
10	D: Bolted, tensioned, grouted, with mesh	11 mths	42 (35)	88.8 (43.2)	22375 (1880)	17170 (3380)	1.20	2.06	11.90	5.08

*Stress and strain values for corresponding plain concrete prisms are enclosed in parentheses.

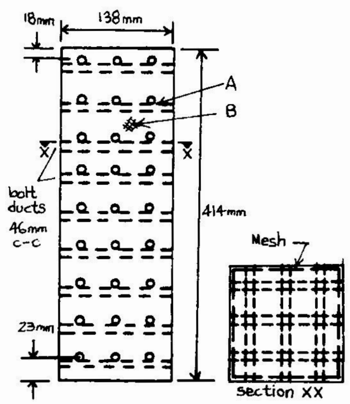


Fig. 1 Details of specimen

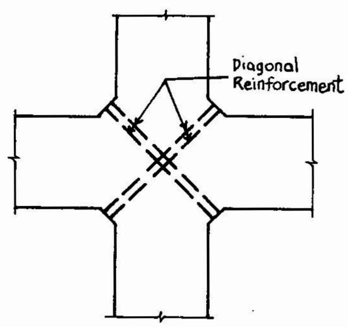


Fig. 8 Possible use of bolts in beam-column joint (schematic)

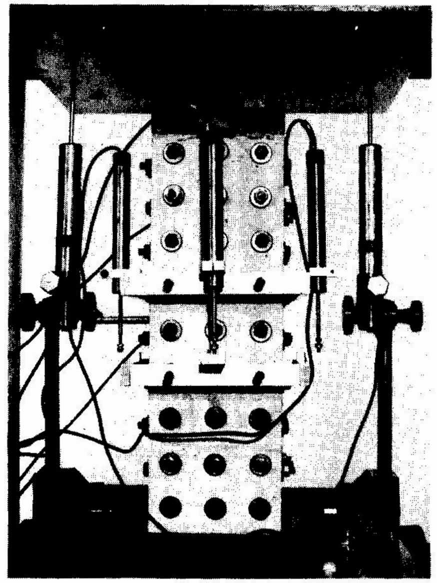
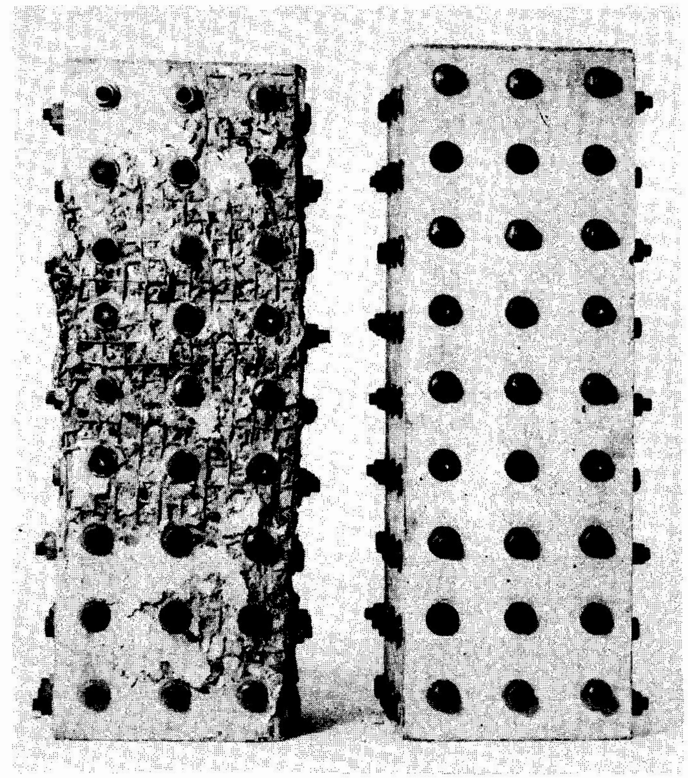


Fig. 2 View of typical specimen in testing machine.

Fig. 3 Ungrouted and untensioned specimen before (right) and after (left) test.



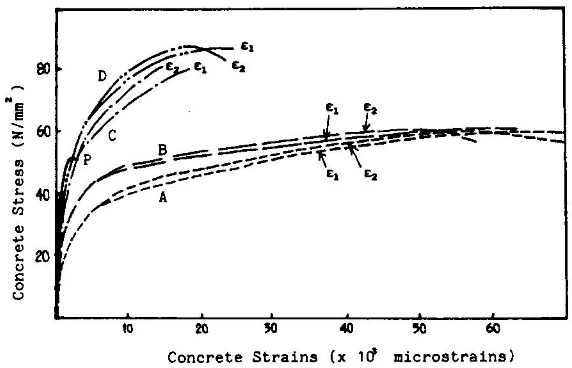


Fig. 4 Typical stress-strain curves for various specimen curves.

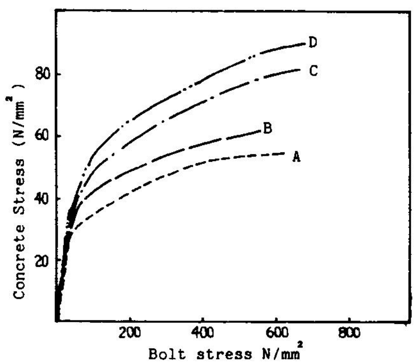


Fig. 5 Typical bolt stresses during loading.

KEY

A: Ungrouted, untensioned
B: Ungrouted, tensioned
C: Grouted, untensioned
D: Grouted, tensioned
P: Plain concrete
ε_1 : Middle-third strain
ε_2 : Between-platens strain

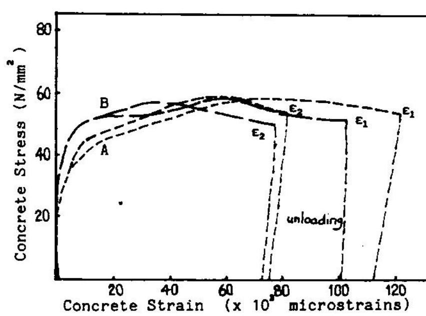


Fig. 6 Mean stress-strain curves for post-ultimate loading

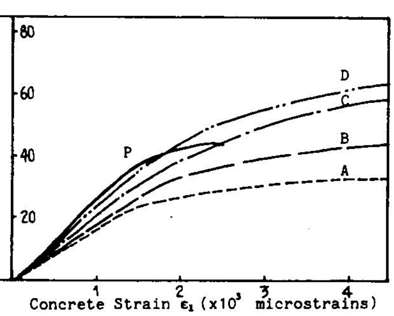


Fig. 7 Typical stress-strain curves at low loads.