SEISMIC RETROFIT OF SQUARE RC COLUMNS USING PRESTRESSED NON-LAMINATED CFRP STRAPS

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ABSTRACT :

Many existing columns have insufficient transverse reinforcement leading to premature collapse during an earthquake. One solution that has become very popular in the last couple of years is confinement with fibre reinforced polymer (FRP) wraps or jackets. Whereas confinement is most efficient when applied to circular columns, it is usually much less effective when applied to columns having a square or rectangular cross section because a significant portion of the cross section remains unconfined. In this paper, an innovative method is presented to confine rectangular reinforced concrete columns using non-laminated CFRP straps. The CFRP straps can be either unstressed at the beginning or prestressed. Tests were carried out at the Swiss Federal Laboratories for Materials Testing and Research (Empa) on three large scale columns (2.0 m high with a cross section of 0.4 m x 0.4 m). The first column was the unconfined reference column, the second column was confined with prestressed non-laminated CFRP straps and the third column was confined with non prestressed non-laminated CFRP straps. The test results show no or only a small increase in strength but a significant increase in the deformation capacity of the confined columns with respect to the unconfined column. This behaviour is in fact desired for seismic loading to ensure life safety of the structure. Finally, a simple analytical model is introduced to predict the axial stress-strain relationship.

KEYWORDS: confined concrete, rectangular columns, CFRP straps, deformation capacity

1. INTRODUCTION

Many reinforced concrete columns in existing structures have insufficient transverse reinforcement leading to low flexural strength and ductility. This could cause a fatal collapse during an earthquake and hence upgrading of these structures has become indispensable. In recent years, external confinement by wrapping and bonding FRP sheets and straps has become increasingly popular, mainly due to their high strength and ease of application. Extensive research on the external confinement of columns has shown that the external wrapping with FRP is a very efficient method to increase the strength and deformation capacity of circular columns. For rectangular columns, however, external confinement is usually much less efficient due to the difficulty of effectively confining the whole section (Karam & Tabbara 1999; Gosh & Sheikh 2007; Mirmiran et al. 1998; Zarafshan et al. 2006). The resulting increase in strength and ductility is rather limited.

At the Swiss Federal Laboratories for Materials Testing and Research (Empa) a research program was launched aiming at the development of a new confining technique for square reinforced concrete columns under seismic loading that is simple to apply and does not need a large quantity of FRP material. This new, cost-effective technique consists of confining the columns with non-laminated CFRP straps. Prestressed and non-prestressed straps were investigated experimentally. To reduce material costs, the confinement ratio was kept as low as possible. So far the first part of the experimental investigations consisting of uniaxial load tests were carried out and the test results are presented in terms of failure modes and axial stress – strain relationships.

2. TEST SET UP

Three large scale reinforced concrete columns were tested under increasing uniaxial loading. The columns had a height of 2 m and a square cross section of 400 mm x 400 mm (Fig. 1). Column (1) was used as the reference column and was tested without confinement. Column (2) was confined with prestressed non-laminated CFRP straps and column (3) was confined with non-prestressed non-laminated CFRP straps.

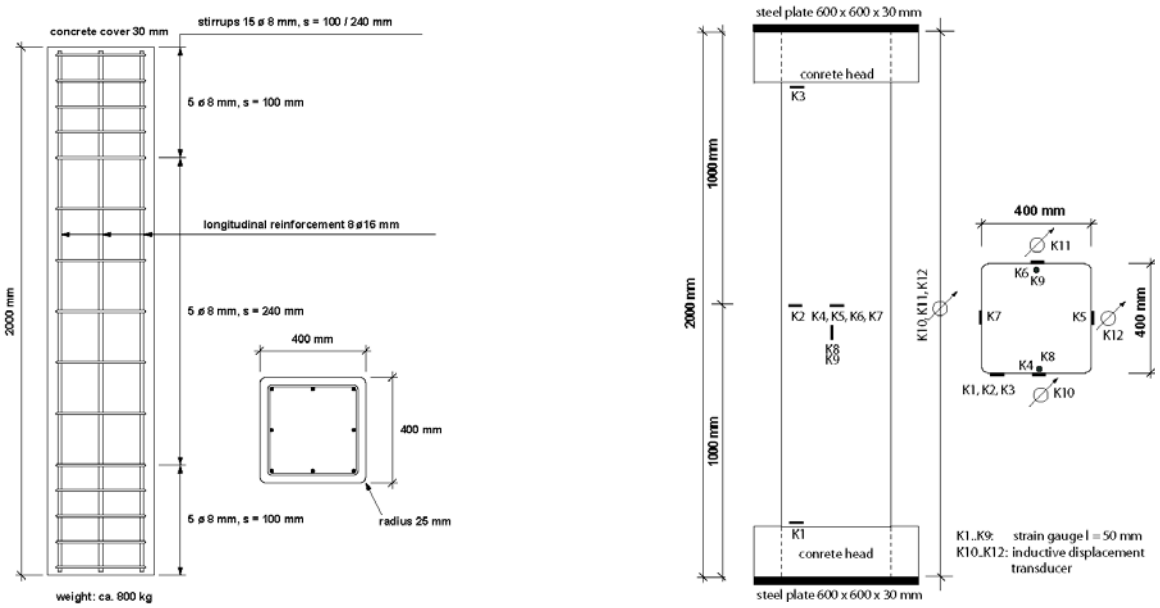

Figure 1 Dimensions and reinforcement of columns (left) and instrumentation (right)

At both ends of the columns 600 mm x 600 mm x 180 mm heads were cast for a better load distribution and to prevent local failure (Fig. 1 right). The concrete heads had a cube compressive strength after 28 days of about 71 MPa. For the columns themselves, a concrete with a low compressive strength of about 20 MPa was chosen to represent the condition of existing columns. The low concrete quality was produced in the laboratory by using 0.75 mass percent air entraining agent. The corresponding concrete properties at the date of testing, 35 days after casting, are shown in Table 1.

Table 1 Concrete cube compressive strength after 35 days

	Column (1) without confinement	Column (2) with prestressed CFRP straps	Column (3) with non prestressed CFRP straps
f_{c0} [MPa]	19	20	20

Table 2 Mechanical properties of reinforcing steel (mean value of three tests)

bar diameter [mm]	yield stress [MPa]	ultimate strength [MPa]	strain at ultimate strength [-]
16	505	598	0.15

Table 3 Mechanical properties of CFRP straps

thickness [mm]	width [mm]	E-modulus [GPa]	ultimate strain [-]
0.125	30	131	0.0183

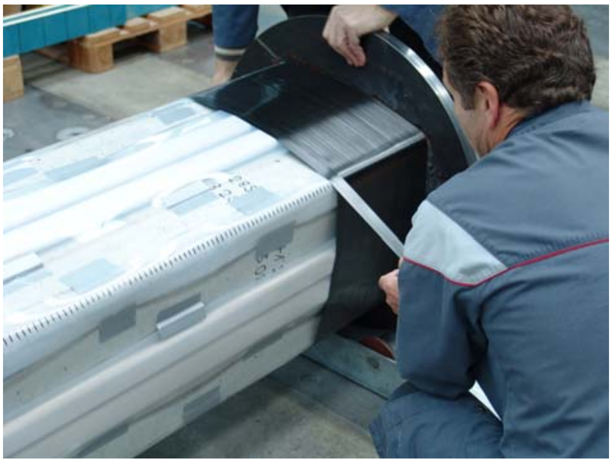

Figure 2 Wrapping of CFRP straps of column (3)

The columns were reinforced in the longitudinal direction by 8 Ø 16 mm bars. This corresponds to a reinforcement ratio of 1%. For the shear reinforcement 15 Ø 8 mm stirrups with a maximum spacing of 240 mm were used (Fig. 1). The properties of the reinforcing steel are given in Table 2.

The non-laminated CFRP straps were made with Toray T-700 fibres using a thermoplastic polyamide resin. The fibre content ranged between 55 and 60% with a mean value around 57%. The mechanical properties of the CFRP straps are given in Table 3.

The confinement technique consists of the following steps: Before the CFRP straps were wrapped around the columns two hoses with an outer diameter of 42 mm were fixed at each side of the columns. Then a plastic film was introduced over the hoses and the concrete surface in order to prevent premature damage of the CFRP straps due to concentrated stresses caused by the crushed concrete. The CFRP straps were wrapped carefully around the perimeter of the column (Fig. 2). No bond existed between the straps and the concrete surface except at their ends, where the straps were fixed onto the concrete surface using epoxy resin. Each CFRP layer overlapped the previous layer by about 20 mm. The wrapping was performed two times. Thus, in the end, the column was confined by 6 layers of CFRP straps with a total thickness of 0.75 mm. For column (2) the hoses were filled with mortar after the wrapping so that the CFRP straps were prestressed (Fig. 3). For column (3) the hoses were filled with mortar prior to the wrapping, so that the CFRP straps were initially unstressed.

The confined columns (2) and (3) were instrumented for displacement and strain measurements according to Figure 1 (right). In total, nine strain gauges (K1-K9) and three inductive displacement transducers (K10-K12) were used. Strain gauges K1-K7 measured the strain of the CFRP straps whereas strain gauges K8 and K9 were used to record the strain of the internal longitudinal steel reinforcement. For column (2), strain gauges K1-K3 were applied before the CFRP straps were prestressed. This allowed control of the strain in the CFRP straps during prestressing (Fig. 3). For the reference column (1), only strain gauges K8 and K9 and the displacement transducers K10-K12 were used.

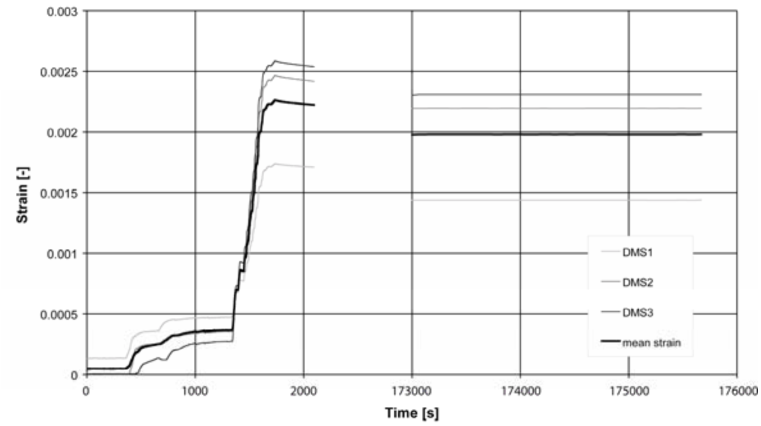

Figure 3 Strain in the CFRP straps at strain gauges K1-K3 during pre-stressing and after 48 hours

The columns were subjected to monotonic uniaxial compression using a 20'000 kN testing machine. In the quasi-elastic range, the force was applied through load control with a loading rate of 1.5–2.0 kN/s. As the behaviour became nonlinear, the load was applied under displacement control at a rate of 0.03–0.04 mm/s.

3. TEST RESULTS

Failure modes

The reference column (1) showed a typical behaviour of an unconfined column with fracture of concrete together with buckling of the longitudinal reinforcement after the peak compressive strength was reached (Fig. 4 left). Columns (2) and (3) confined with non-laminated CFRP straps also experienced cracking of concrete together with buckling of the longitudinal reinforcement at very small deformations. However, failure of columns only occurred after extensive additional deformations by rupture of the CFRP straps (Fig. 4 centre and right).

Figure 4. Observed failure modes of columns (1) to (3) from left to right

3.2. Axial stress-strain relationship

Fig. 5 shows the axial stress-strain behaviour of the three columns. The axial stress was obtained by dividing the applied load by the concrete area of the column section. The axial strain is the mean value of the measured deformations at strain gauges K10-K12 divided by the total height of the columns (2 m). The observed failure mode of reference column (1) is also visible in the axial stress-strain relationship: After the peak compressive strength of 20.0 MPa was reached the column failed by fracture of concrete together with buckling of the longitudinal reinforcement. The column could not sustain any more loading. Also columns (2) and (3) confined with non-laminated CFRP straps showed a drop in the strength after the first peak of 23 MPa and 21 MPa respectively. The drop was larger for column (3) with non-prestressed CFRP straps than for column (2) with prestressed CFRP straps. The strength drop was followed by an initial softening behaviour that transformed progressively into a hardening behaviour. Both columns only failed after extensive additional deformations with axial strains of 0.03 and 0.057 respectively.

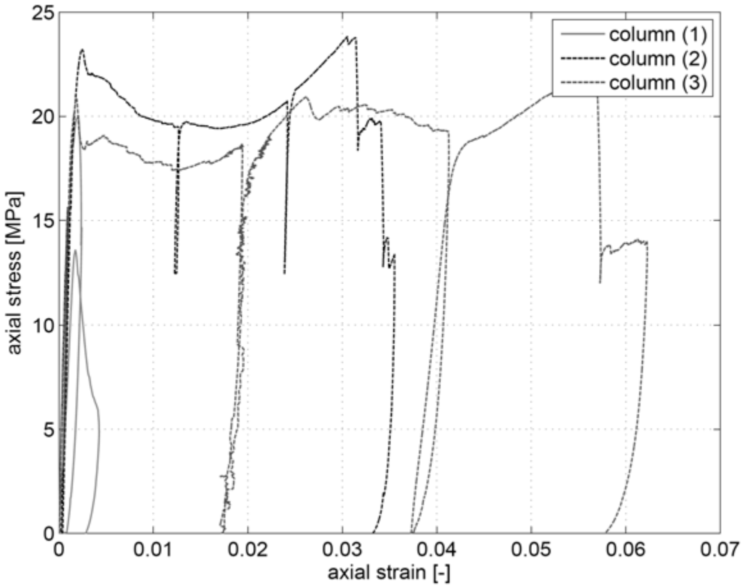

Figure 5 Measured axial stress-strain relationships of columns (1) – (3)

4. INTERPRETATION OF TEST RESULTS AND IMPLICATION FOR SEISMIC RETROFIT

The confined columns show a very large deformation capacity, larger in fact than can be observed with more conventional confinement techniques. However, this large deformation capacity is accompanied by a strength drop after the first peak and a softening behaviour. The reason for this lies in the fact that the CFRP straps were not in full contact with the complete concrete surface. Hence, the initially unconfined concrete fails in compression at an axial strain of about 0.002 and 0.0026 for columns (2) and (3) respectively, which corresponds to the strain at the first peak. After failure in compression the concrete spreads laterally, filling the gaps between the concrete column and the CFRP straps, the longitudinal reinforcement starts to buckle. This leads to a sudden drop in the axial strength. While the unconfined reference column (1) cannot sustain anymore loading beyond this point, the confined columns (2) and (3) experience softening behaviour until the gaps are filled with concrete. Once the gaps are filled with crushed concrete, further lateral spreading of the concrete starts to strain the CFRP straps creating a confinement effect. The axial strength increases again until at very large axial strains the columns fail by rupture of the CFRP straps.

The axial strain capacity of column (2) is smaller than those of column (3). Even though the prestressing of the CFRP straps reduces the available strain in the CFRP straps of column (2), this alone cannot explain the larger axial strain capacity of column (3). Further investigation are therefore needed.

For a satisfactory behaviour of structures under seismic action, softening behaviour should be prevented. However, in the case of the proposed confinement technique the softening behaviour of the confined columns is followed by a hardening behaviour. Hence, progressive failure leading to instability is prevented. The proposed confinement technique could be therefore of great relevance to the seismic retrofit of existing structures when life safety is of concern. As the confinement technique accepts large damage of the reinforced concrete columns, it is not suitable for cases where serviceability criteria are predominant and therefore, deformation control is of concern.

5. SIMPLE ANALYTICAL MODEL

Existing models to calculate the axial stress-strain relationship of FRP confined reinforced concrete columns cannot capture the characteristics of the proposed method. The reason is mainly that existing models usually assume that the strain in the confinement increases as soon as the axial strain increases. Clearly, this is not true for the proposed confinement technique where the tests have shown that the gaps between the concrete surface and the CFRP straps have to be filled with crushed concrete before strain in the CFRP straps developed.

A simple model is therefore proposed to estimate the deformation capacity of the confined columns. The model is in fact a modification of the well known model by Spoelstra and Monti (1999) with a new relationship between lateral strain and axial strain. The proposed relationship is a bilinear function. In the first region, the lateral strains remain constant at the prestrain level ε_{lo} for the case of prestressed straps or zero in the case of non prestressed straps. The second region shows a linear relationship between the lateral strains and the axial strains (Fig. 6). It should be noted that in order to apply the model by Spoelstra and Monti to square columns, a parameter for the effectively confined area is introduced. This parameter is derived following the pulley model by Karam and Tabbara (2005).

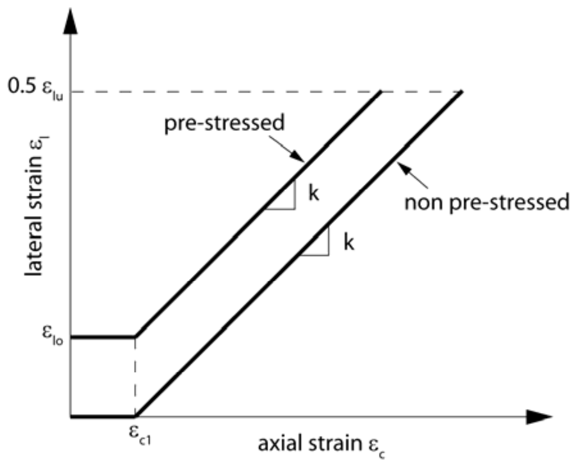

Figure 6 Proposed bilinear lateral strain – axial strain relationship

Figure 7 shows a comparison of the axial stress-strain relationship derived with the simple model with the measured axial stress-strain relationship for column (2) and Figure 8 shows the comparison for column (3).

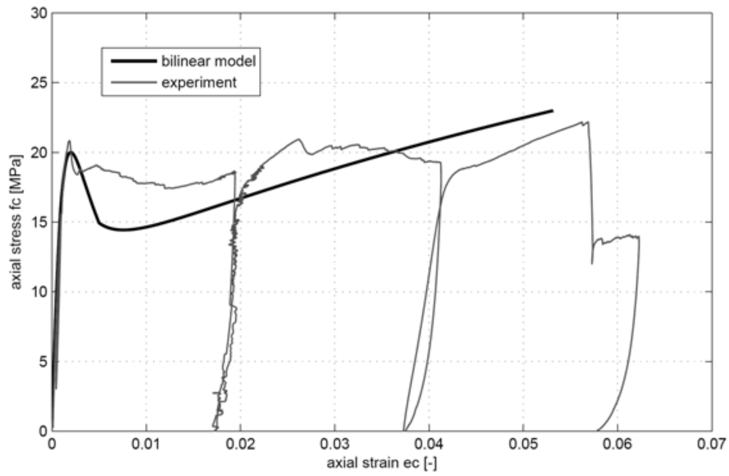

Figure 7 Measured and calculated lateral strain – axial strain relationships for column (2)

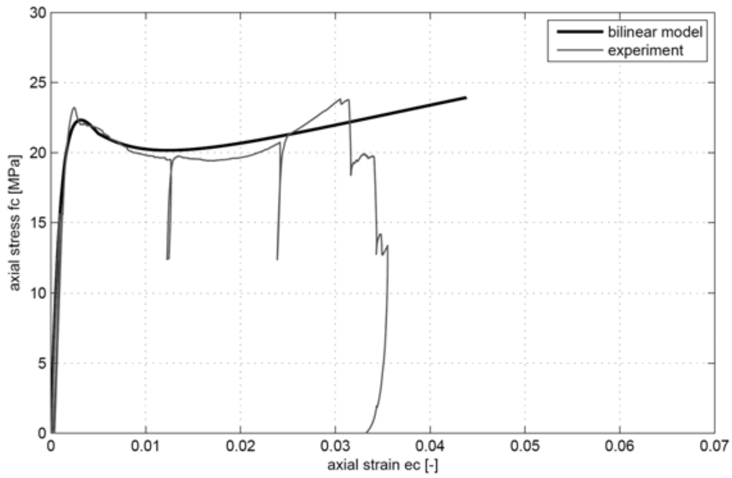

Figure 8 Measured and calculated lateral strain – axial strain relationships for column (3)

6. CONCLUDING REMARKS

A new confinement technique for square reinforced concrete columns is proposed using non-laminated CFRP straps. Three large scale axial load tests have been performed at the Swiss Federal Laboratories for Material Testing and Research (Empa) that have shown that this confining technique can lead to very large deformation capacities. This is mainly due to the gaps between the concrete surface and the CFRP straps which have to be filled with crushed concrete before the confinement is activated. This delayed activation results in a load drop after the first peak followed by softening behaviour. This softening behaviour, however, is not perilous as it is followed by a hardening behaviour. Due to the large deformation capacity the proposed confinement technique might be well suited for seismic retrofit of buildings where the life safety is a concern. In order to confirm this, the behaviour of square columns confined with non-laminated CFRP straps under the combined action of axial loading and bending moment shall be studied at the Empa. Further investigation concern the effect of prestress and the practicability of the prestressing.

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