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FRP SEISMIC STRENGTHENING OF CONCRETE STRUCTURES

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Abstract: This paper presents the experimental work carried out on a full scale concrete frame strengthened with Fibre Reinforced Polymer (FRP) composites. The frame was damaged, strengthened with FRP reinforcement and re-tested to assess the effectiveness of the strengthening technique. The natural frequencies of vibration, displacements, velocities and accelerations for both the unstrengthened and strengthened frame were recorded and compared.

1. Introduction

Seismic strengthening of reinforced concrete (RC) frames represents an important challenge for engineers in countries with seismic risk. Since the 1995 Kobe earthquake, FRP composites started being used extensively for the repair and strengthening of RC members in seismic zones (Priestley, 1995; Seible, 1997). Unique properties of these materials, such as high strength, light weight, corrosion resistance, ease of fabrication and application, have attracted the attention of many engineers involved in the strengthening design (Hollaway,1999). However, there are concerns regarding the ability of FRP composites to dissipate energy. This concern is misguided since FRP materials are normally used to confine concrete columns (Fig.1) rather than provide flexural reinforcement. For a confinement material, the objective is to prevent the lateral dilation of concrete and, hence, the lack of ductility of FRP is not necessarily an issue (Triantafillou, 2001; Priestley, 1995).

This paper presents the experimental work carried out on a RC frame strengthened with FRP composites. The effectiveness of this strengthening technique is assessed.

This work formed part of a wider research program within the EU TMR Network ConFibreCrete and the EU Ecoleader research project.

2. Experimental work

A full scale, two-storey RC frame was constructed, damaged on an earthquake simulator and repaired using carbon fibre reinforced polymer (CFRP) material. The storey height of the frame is 3.3 m and the span is 4 m. The earthquake simulator is a six degree-of-freedom shake table, with a maximum payload of 100 tons and a maximum displacement in the horizontal direction of 250 mm.

Fig. 1 FRP confinement of concrete columns

2.1. Bare (unstrengthened) frame

Initially, the bare frame (Fig. 2) was subjected to white-noise test, with frequencies varying between 0.5-50 Hz and a low acceleration level (max. 0.05g) in order to measure the natural frequencies of vibration.

The bare frame was afterwards damaged, being subjected to five uni-directional seismic tests with the maximum accelerations 0.05g, 0.10g, 0.2g, 0.3g and 0.4g. The natural frequencies of vibration of the frame were measured after each seismic test. The first two natural frequencies of vibration of the undamaged and damaged bare frame are presented in Table 1.

No damage was observed after the first two seismic tests. First damage occurred during the 0.2g seismic test. Diagonal cracks appeared at the joints of the 1st floor (Fig.3) and horizontal cracks formed under the joints of the 2nd floor. Some new horizontal cracks appeared above the joints of the 1st floor and in the columns during the 0.3g seismic test. During the last seismic test (0.4g), new cracks developed along the height of columns and spoiling of concrete was noticed at the base of one column.

Fig. 2 Bare frame

Tests	1st freq. (Hz)	2nd freq. (Hz)
White noise	1.90	5.60
0.05g	1.66	4.88
0.10g	1.36	4.30
0.20g	1.07	3.60
0.30g	0.88	2.64
0.40g	0.68	2.54

Table 1. Natural frequencies vibration for the bare frame

2.2. Unstrengthened frame

The damaged frame was strengthened with CFRP unidirectional fabric (TFC®). The fabric is composed of 70% fibers in the warp direction and 30% in the weft direction, having the following characteristics: Young's Modulus 105 GPa, yield stress in tension 1700 MPa, thickness 0.48 mm.

Since the most damaged areas were the joints and the end of the columns, the FRP confinement was applied at these locations (Fig.4). Very little amount of FRP reinforcement was applied at the end of the beams since the aim of the strengthening was to transfer the plastic hinges (zones with concentrated damage) from columns onto beams. In the columns and beams, the FRP material was applied with the fibers in the warp direction parallel to the axis of the members, while at the joints, the FRP confinement was applied at 45^0 to follow the shear (diagonal) cracks.

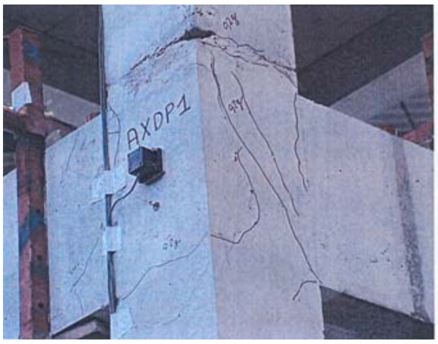

Fig. 3 Joint damage

Fig. 4 FRP strengthened frame

Tests	1st freq. (Hz)	2nd freq. (Hz)
White noise	1.37	4.30
0.05g seismic test	1.27	4.20
0.20g seismic test	1.07	3.61
0.40g seismic test	0.98	3.32
0.50g seismic test	0.88	3.00
0.04g sine sweep test	0.78	3.02
0.08g sine sweep test	0.78	3.00
0.10g sine sweep test	0.78	2.93
0.12g sine sweep test	0.78	3.02
0.14g sine sweep test	0.78	2.93
0.18g sine sweep test	0.68	2.73

Table 2. Natural frequencies of vibration for the strengthened frame

The strengthened frame was firstly subjected to white noise tests with frequencies ranging between 0.5-50Hz, with a low level of acceleration (0.05g) in order to measure the natural frequencies of vibration.

The frame was afterwards subjected to seismic tests with the maximum accelerations 0.05g, 0.20g, 0.4g. and 0.5g. Since for levels of acceleration bigger than 0.5g the displacement of the shake table would exceed the maximum allowed, the seismic tests had to be limited to a maximum acceleration of 0.5g. However, in order to bring the strengthened frame close to failure, sine sweep tests had to be applied to the frame. The sine sweep tests had frequencies ranging between 0.6 Hz and 1.1 Hz and maximum accelerations between 0.04g-0.18g. Natural frequencies of the frame were measured after each seismic and sine sweep test. Table 2 shows the natural frequencies of vibration of the strengthened frame.

No damage was observed after the first seismic test (0.05g). Some level of damage was detected under the FRP strengthening at the base of columns in the 0.20g seismic test. No further damage appeared during the 0.40g seismic excitation. Some new cracks formed in beams (Fig.5) and columns after the 0.50g seismic test. Debonding and tearing of the FRP reinforcement was noticed at joints (Fig.6).

3. Results and discussion

The response in terms of displacements, velocities and accelerations were recorded both for the unstrengthened and strengthened frame. In this paper some of the experimental results are presented.

Figure 7 shows the absolute displacement at the first floor for the unstrengthened frame at the maximum level of acceleration 0.40g and the absolute displacement at the same floor for

Fig. 5 Crack development in beams

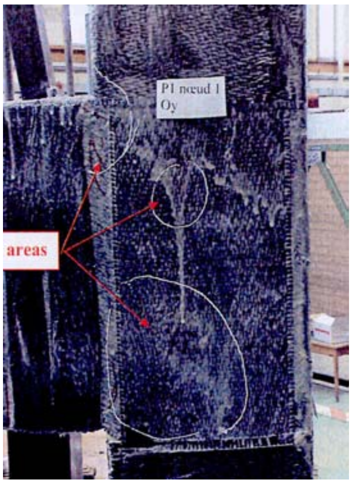

Fig. 6 FRP damage

the strengthened frame at the maximum level of acceleration of 0.50g, respectively.

The maximum relative displacement at the first floor for the unstrengthened frame at 0.4g level of excitation was 67.12 mm, while the maximum relative displacement at the same floor for the strengthened frame at 0.5g level of excitation was 115.64 mm. This is equivalent to an increase in displacement of 72%.

Figure 8 shows the acceleration at the 1st floor of the unstrengthened frame at 0.4g level of acceleration while Figure 9 presents the acceleration at the 1st floor of the strengthened frame at 0.5g level of acceleration.

The maximum acceleration in the unstrengthened frame at the first floor for 0.4g level of excitation was 0.518g and the maximum acceleration in the strengthened frame at the same floor for 0.5g level of excitation was 0.603g, which is equivalent to an increase in acceleration of 16.5%.

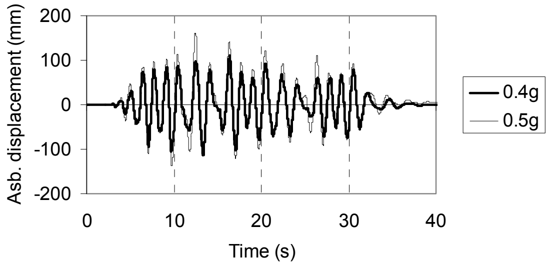

Fig. 7 Absolute displacement at the first floor of the frame

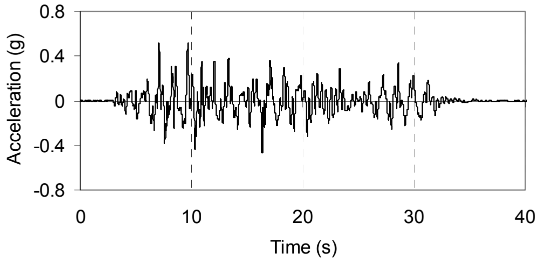

Fig. 8 Acceleration at the 1st floor of the unstrengthened frame at 0.4g

4. Conclusions

Experimental work was carried out on a full scale RC frame strengthened to FRP composites. The natural frequencies of vibration, displacements, velocities and accelerations for both unstrengthened and strengthened frame were recorded and compared.

At the end of experimental testing, a reduction in the fundamental frequency of vibration of 64% and 50%, respectively, was noticed for the unstrengthened and strengthened frame.

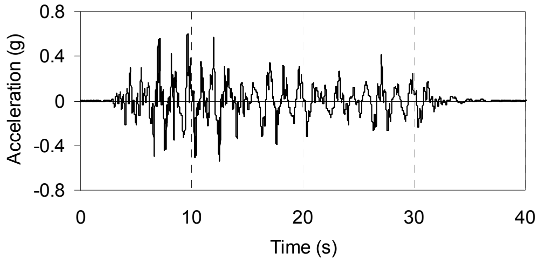

Fig.9 Acceleration at the 1st floor of the strengthened frame at 0.5g

The FRP reinforcement increased the fundamental frequency of vibration of the frame by 50%.
The strengthened frame was noted to resist bigger accelerations. An increase in acceleration at the first floor of 16.5% was noticed compared to the unstrengthened frame.
The displacement at the first floor of the strengthened frame is bigger than the displacement of the bare frame. An increase in relative displacement of 72% was observed. This shows that the FRP strengthening results in a significant increase in ductility.
At the end of the seismic test corresponding to 0.5g level of excitation, significant damage in the beams of the strengthened frame was noticed compared to the damage in columns. This shows that a transfer of plastic hinges from columns into beams might take place.

5. References

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