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Enhancement of Seismic Performance of Steel Frame through CFRP Strengthening

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Abstract

Seismic strengthening is an urgent need for mitigating the high collapse risk of existing and future constructed steel frames during the possible earthquakes in the future. In this study steel frames are strengthened by using externally bonded carbon fibre reinforced polymers (CFRP) composites with varying the layers number of CFRP to mitigate the seismic action on steel frames. Shake table test of bare and strengthened steel frames has been performed. The CFRP strengthening technique improved the stiffness of the steel frames which results less lateral deflection of the steel frames under seismic action and indicates its effectiveness for seismic mitigation of steel frames.

Keywords: steel frame; CFRP; seismic strengthening; no of CFRP layers, shake table test.

1. Introduction

Earthquake is one of the most destructive natural disasters and the reason of extensive loss of human lives and property. Earthquakes is the reason of 1.87 million deaths worldwide in the 20th century and an average of 2,052 fatalities per earthquake has occurred in the world [1].

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Steel frames are becoming very popular in building construction and are widely used in high seismic risk area all over the world [2]. However, in the recent major earthquakes, fracture and brittle failure of welded beam-column joints have occurred [3] [4]. In the Northridge earthquake in 1994, welded beam–column connections had been damaged mostly. From the surveyed structures, at least one welded connection of around 70% of the floors were seriously damaged, whereas only 25% of the connections with no damage. 20% of the surveyed building frames had more than 40% damaged connections [3]. In an early study, three main failure modes in the steel welded beam-column connection has been found namely, flange-Heat Affected Zone, fracture of flange-weld and flange buckling with percentages of 43%, 27% and 16% respectively [4].

Steel moment connections require high strength and ductility to mitigate brittle fracture which is the main failure mode of steel moment connections and [5]. In common practice existing members are welded by steel cover plates for rehabilitation and seismic strengthening of steel connections [6]. But corrosion and fatigue damages can be initiated for welding by steel cover plates [7] as well as it is very difficult task. Carbon fibre reinforced polymer (CFRP) composites are a good alternative to overcome these limitations and have many other advantages (e.g. high tensile strength and strength-weight ratio [8], resistance to corrosion [9] etc.). Externally bonded CFRP reinforcement technique is very effective to improve the ultimate load carrying capacity, impact resistance capacity [10] and stiffness of the beam–column connections [11]. This is an established solution towards improving the strength and stiffness characteristics of beam-column connections [12]. Hence, the purpose of that is to mitigation of seismic action on steel frame by CFRP wrapping.

Seismic mitigation of structure is normally carried out based on two generic theoretical considerations. First one is resonance, which means to move the fundamental natural frequency of the structure from the outside of the dominant frequencies range of common earthquakes. After CFRP wrapping the structure will stiffer and therefore fundamental natural frequency will shift outside from the dominant frequencies range of earthquakes. The second theoretical considerations are plastic hinge within strong column-weak beam concept: The second theoretical basis for CFRP wrapping is to prevent the formation of plastic hinge at beam-column junctions during the potential failure if any. The CFRP wrapping therefore must enable to form the potential plastic hinge, if any, to occur on the beam, but at a location away from beam column junctions. As the stiffness of the frames has been enhanced after CFRP wrapping, in the general result displacements has been reduced based on the second generic theoretical considerations.

This study focuses on preliminary experimental investigation on the effects of CFRP strengthening of small scale two-story one-bay steel frames subjected to seismic action. The beam–column connections are treated as the most critical area in a moment resisting frame. In this study, the simpler form of harmonic excitation is used to represent seismic action [13]. The number of layers of CFRP has been varied to investigate its effects on the amount of deflection reduction.

2. Experimental Program

2.1. Materials

Steel Frames are constructed by using hot rolled structural steel of grade 300PLUS supplied by OneSteel Limited, Brisbane, Australia. The flat steel plate used as slab and the flat steel bar used as column were manufactured as per AS/NZS 3678:2011 [14] and AS/NZS 3679.1:2010 [15] respectively. The mechanical properties of the steel are listed in Table 1 and obtained from the manufacturer.

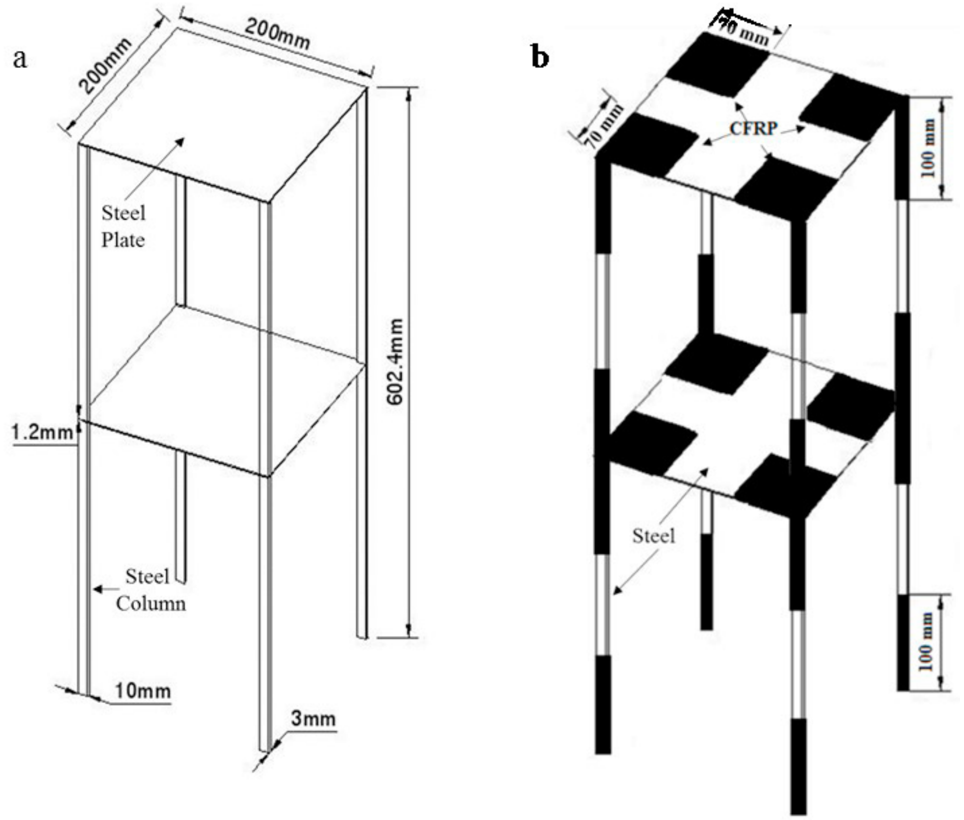
Table 1: Material properties

Property	Steel	CFRP	Adhesive
Density (kg/m^3)	7850	1700	-
Elastic modulus (GPa)	200	125	2.028
Tensile strength (MPa)	-	3800	25
Poisson’s ratio	0.25	0.28	0.32

For seismic strengthening normal modulus CFRP composites sheets with epoxy adhesive has been used in this study. Unidirectional CF130 of nominal thickness and fibre weight 0.176 mm 300 g/m^2 respectively was used as CFRP composite. The. MBrace saturant of two-part epoxy resin was used as adhesive. CFRP composites sheets and epoxy adhesive were supplied by BASF construction chemicals, Brisbane, Australia. The CFRP and adhesive mechanical properties are shown in Table 1 and obtained from the one of the Authors previous study [16].

2.2. Test Specimens and Retrofitting Schemes

Design and Manufacturing Centre (DMC) of Queensland University of Technology (QUT) were manufactured the four steel frames for the testing as per AS/NZS 5131:2016 [17]. The models were of a small-scale by considering the limitations of the shake table and the Laser Displacement Sensor (LDS) for measuring deflection (must be less than 30 mm) and the models should fit onto the shake table. The first frame remained unstrengthen used as the bare control specimen and denoted as BF. The second frame had strengthened by applying one layer of CFRP in the critical regions of steel frame and denoted as SF1, the third frame had strengthened by two layers of CFRP (the second layer applied directly over the top of the first layer) and denoted as SF2 and the fourth frame had strengthened by applying one layer and two layers of CFRP in the column and plate of specimen respectively and denotes as SF4. All frames were two story frames with one bay of span length 200 mm in both direction and the story height of both bottom and top storeys were 300 mm. The cross section of the column was 10-mm×3 mm and the thickness of the steel plate used as slab was 1.2 mm. The critical connections regions of the frames have been wrapped by CFRP, across 100 mm from the connections, both above and below the column and across an area of 70x70mm from the connections on the top and bottom of the plate. Figure 1(a) shows the dimensions of the bare specimen, Figure 1(b) shows the CFRP wrapping scheme and Figure 1(c) is a photo of the four prepared specimens that were tested.



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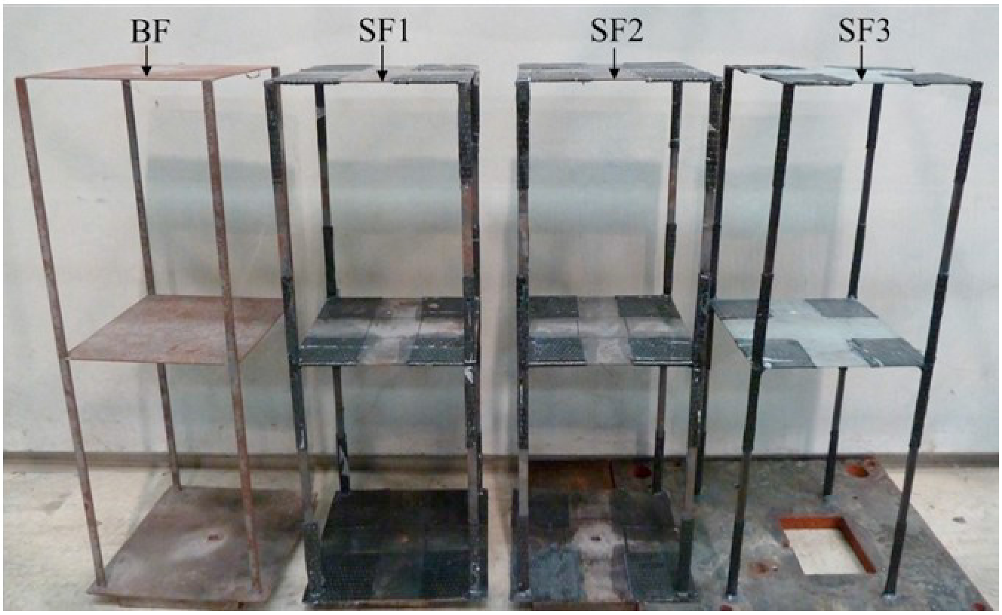

Fig. 1. Details of Specimens (a) dimensions of the bare specimen (b) CFRP wrapping scheme (c) prepared specimens for testing

2.3. Specimen Preparation and Strengthening Process

The first and one of the most important stage of the CFRP strengthening process is Surface preparation which needs to ensure appropriate bonding between the steel substrate and CFRP sheet. Sandblasting technique, to remove impurities and obtain a uniform surface [18], has been used to prepare the wrapped surface of the steel frames. Sandblasting was done by using a granite abrasive system and the average grit size was 0.425 mm in the DMC of QUT. The sandblasted specimens were cleaned with acetone to remove dust particles and week layers [19]. MBrace 3500 primer has been applied in the cleaned sandblasted specimens before applying adhesive. First the two part of primer of MBrace 3500 mixed properly and applied on the surface of the specimens with brush. After 1 h curing, the two-part epoxy adhesive has been applied. The two part of epoxy (Part A and Part B) adhesive were mixed around 5 min for getting a homogeneous mixer and the mix was applied on the top of primer-coated steel surface. The CFRP sheets were trimmed based on the wrapped area and CFRP orientation. The wrapped CFRP sheets were rib rolled to remove entrapped air bubbles and obtain a uniform epoxy/CFRP laminate thickness by using an appropriate rib roller in the direction of CFRP fibres. Rib rolling was performed until the CFRP fabrics were completely saturated to ensure bleeding of adhesive through the laminates. Through this process, a composite epoxy/CFRP plate will be formed after curing the specimens. The wrapping process was carried out within the pot life of the adhesive, so that workability of the epoxy resin could be used effectively before becoming hardened. In case of multilayer strengthening, the second layer was wrapped consecutively following the same method as the first layer. The multilayer wrapping process was completed on the wet surface of first wrapped layer; thus, after curing, they act as a single composite plate of epoxy/CFRP laminate. Wrapping the specimens with masking tape immediately after the strengthening work has been done, which is very effective for preventing premature debonding and getting a uniform thickness of CFRP/epoxy laminate through the length of wrapping [20]. The masking tape was removed from the specimens after 24 hours of curing. Then the specimens were cured again for at least 2 weeks before the testing [21].

2.4. Test Setup and Instrumentations

A uniaxial shaker table in the Banyo Pilot Plant Precinct of QUT, Australia has been used for shake table test. The size of shaker table is 1.5 m × 1.5 m which has 1000 Kg limitation of test specimens weight. The maximum displacement and acceleration capacities are ±75 mm and 1.0g respectively in the one horizontal direction. The time histories responses of the steel frames were observed by the shake table testing. The displacements of the base plate, the tip first level and the tip second level i.e. tip of the structure were measured by positioning three laser displacement sensors (LDS). The displacement measurement capacity of used LDSs is up to 0.001 mm accurately for a 200 Hz maximum frequency. These LDSs were attached in a rigid frame (fixed with the ground) to measure the relative displacements from the ground. To verify the accuracy of the input acceleration an accelerometer sensor was attached on the base plate of the shaker table and a good validation was observed. The layout of the LDS, accelerometer sensor and experimental setup are shown in Figure 2. All test data was recorded simultaneously by using a data acquisition system.

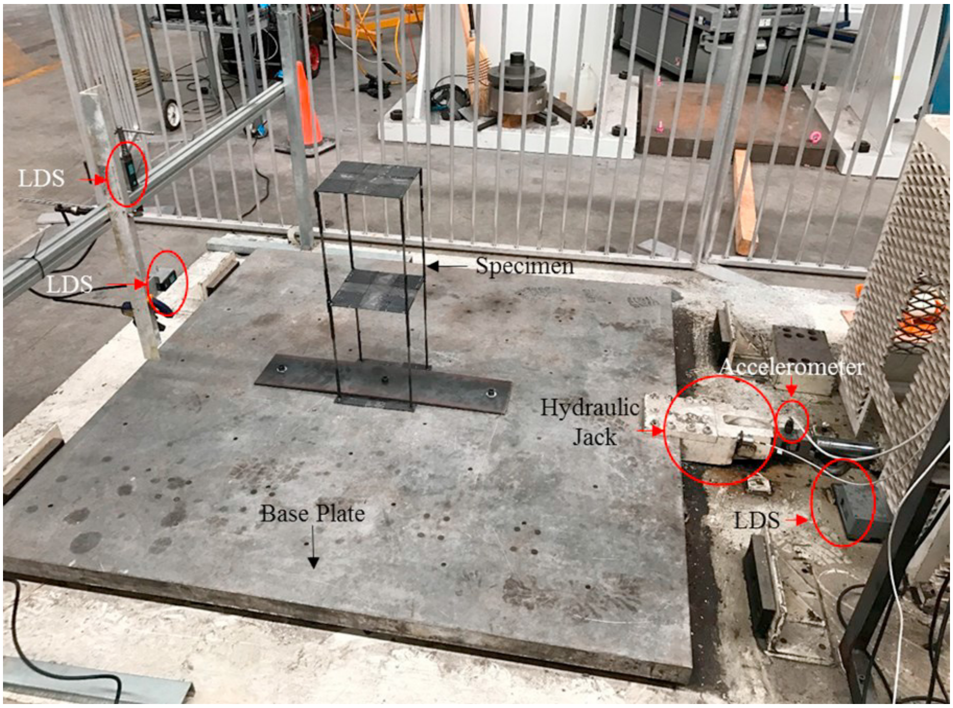

Fig. 2. Experimental set-up

Considering the displacement limits of the shake table and the natural frequency of steel frame model, an ideal sinusoidal wave with 10 mm amplitude and 5 Hz frequency was used as seismic action, as derived below [22]:

$$Accelaration = A \times \left(\frac{2\pi}{T}\right)^2 \times \sin\left(\frac{2\pi t}{T}\right)$$

Where; Amplitude, A = 10 mm, Time step = 0.01s, Period, T = $\dfrac{1}{Frequency, f} = 0.2$

A steel plate of high strength was placed over the base plate of the frame, shown in figure, and bolted to the base plate of the shaker table, simulating the frames being fixed with the ground. The LDSs had been calibrated after fixing the frames with the shaker table. Then the horizontal acceleration had been applied along the weaker axis of the specimen for 10 seconds through a hydraulic jack. The remaining frames were tested by following the same process. The frames were tested for investigating the capability of CFRP strengthening to minimise lateral deflection, not for failure.

3. Results

The top lateral deflection is the single most important parameter to evaluate the seismic behaviour of a steel frame structure [23]. The time-top lateral displacement responses curves of the bare and strengthened steel frames are shown in Figures 3-6. Figure 7 shows the comparisons of the maximum lateral displacements at each floor level of the bare and strengthened frames from the shake table testing.

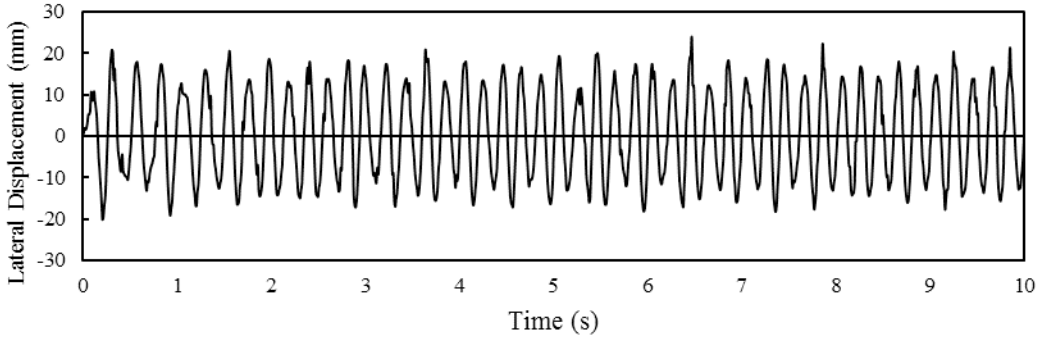

Fig. 3. The top lateral displacements of bare specimens

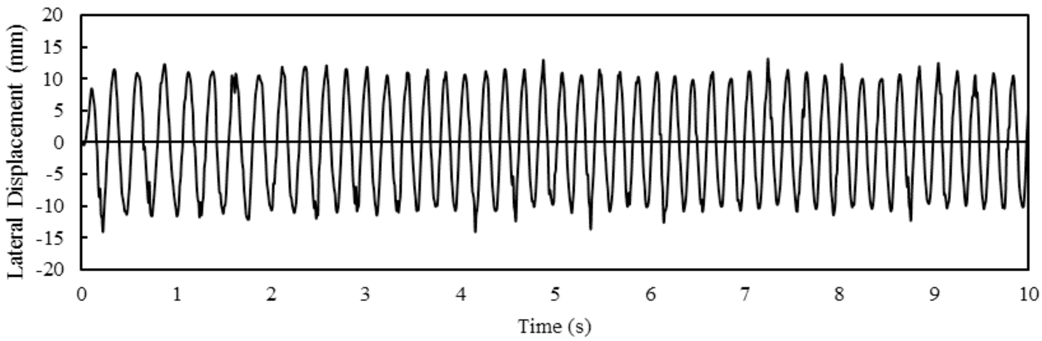

Fig. 4. The top lateral displacements of strengthened frame with 1 layer of CFRP

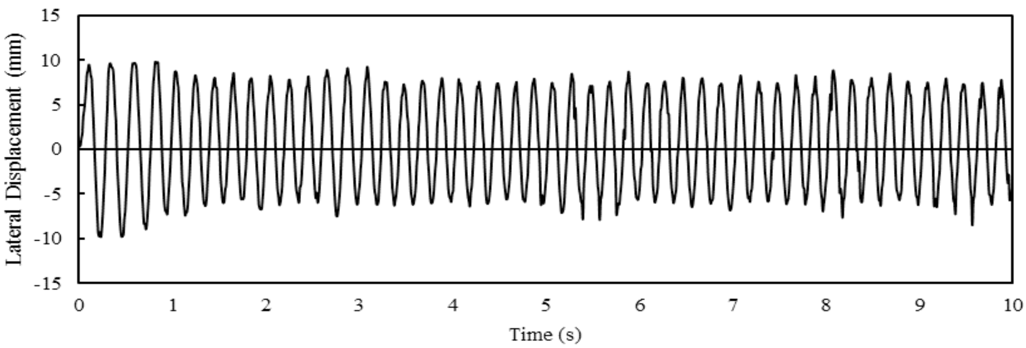

Fig. 5. The top lateral displacements of strengthened frame with 2 layers of CFRP

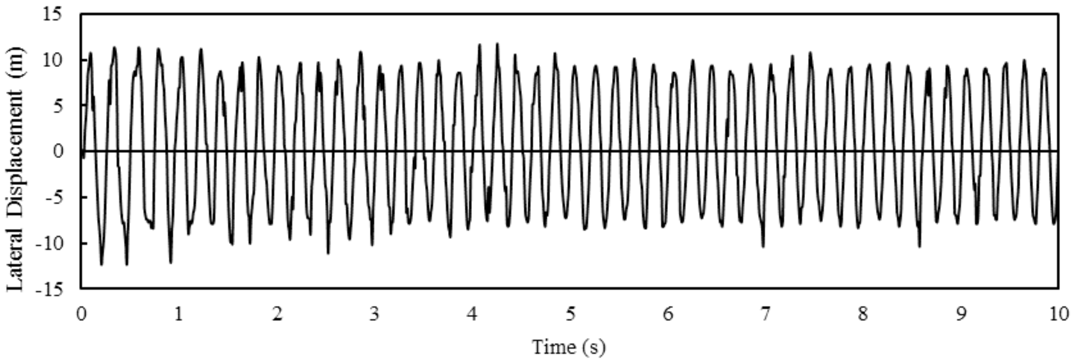

Fig. 6. The top lateral displacements of strengthened frame SF3

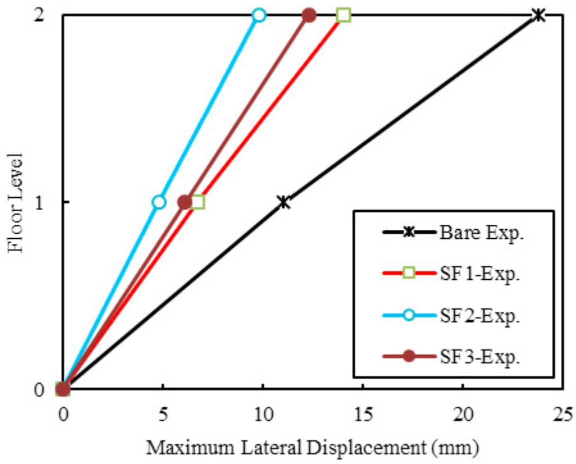

Fig. 7. Comparison of maximum lateral displacements at each floor level

After the wrappings the steel frames have strengthened with increasing its rigidity as well as its stiffness and hence its natural frequency based on theoretical considerations (i). From the Figures 3-6, it is clear that the strengthened frames displace far less than the unstrengthen frame due to the CFRP strengthening under seismic action. CFRP wrapping technique has been enhanced the stiffness of the steel frames and the tip lateral deflections of the steel frames strengthened by one layer and two layers of CFRP have been reduced by 41% and 59% respectively based on theoretical considerations (ii), which proves the effectiveness of using CFRP wrapping in steel structures.

4. Conclusions

The behaviour of CFRP strengthened steel frames subjected to seismic action has been investigated in this paper through experimental testing. From the experimental results it is clear that the CFRP strengthening technique is very effective to enhance the seismic performance of steel frame and improving seismic mitigation capacity of steel frame. CFRP strengthening technique makes the frames stiffer and reduced the lateral displacement under the seismic action. The stiffness of the frames are gradually increased with increase of the no of layer of CFRP composites under the seismic action. Thus, the lateral displacements reduced gradually with the increase of the no of layer of CFRP composites. After strengthening the steel frames with one layer and two layers of CFRP composites, the tip lateral deflections of strengthened frames have been reduced by 41% and 59% respectively under the seismic action and prove the effectiveness of CFRP strengthening technique for enhancing the seismic performance of steel frame.

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