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RESPONSE OF REPAIRED FUSE BEAMS TO DYNAMIC TESTING

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Abstract. *Controlled energy distribution is desirable for structures subjected to severe earthquakes. EC8[1] prescribes (for steel structures) that reduced beam sections may behave like a fuse that protects beam-to-column connections against early fracture (cl. B.S.3.), provided that they can develop the minimum rotations specified. Unlike common steel structures, innovative types of seismic resistant steel frames have been proposed, with dissipative fuses, where only damage will occur. Fuses are designed to be easily replaced. They usually consist of steel hollow sections. In the present paper, used hollow beams, that had suffered strength degradation of more than 50% were filled with cement based repair mortar (f_{cd} =35 MPa), forming concrete filled composite beams (CFCBs) and were retested, without any other kind of repair. CFCBs are reported to have demonstrated higher axial load capacity, better ductility performance, larger energy absorption capacity and lower strength degradation than conventional reinforced concrete and steel hollow section columns. This became apparent by the results or the tests achieved by the experiments; bearing capacity of fuse beam was practically restored to its initial value when the damaged side of the initial beam was subjected to tension, while it increased to about 2.5 times its initial value, when the damaged side is subjected to compression. Increase of energy dissipation per loading cycle was also remarkable (increase about 150%). Calculation of the stiffness of the fuse beam is performed, as it varies with the imposed displacement. Its effect on the eigenperiod of the main structure is discussed. The deformation limits that the cement based repair mortar has reached are calculated. Ideas for further research on the subject are proposed.*

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1 INTRODUCTION

Design against earthquakes combines sufficient strength, stiffness and ductility for structures to be built. Ductility is connected to inelastic deformation of members [1].

Instead of potentially permitting such deformation to all members, effective structural design could exclude primary members of damage, by leading it to secondary members or, even better, to disposable special members. The late ones can act as “fuses”, in case of extreme loading; damage will occur to them only and can be easily replaced after the incident.

Usually, fuses are hollow steel members, welded with plates at both ends. They are connected to other structural members via bolts, so that they can be easily (and immediately) replaced after earthquakes. Bolts and plates are overdesigned, in order to assure that damage will occur at the hollow member only.

Relevant full scale tests have been performed at the Laboratory of Steel Structures of the National Technical University of Athens in the context of the "MATCH" research program, in addition to the tests that were performed in the previous "FUSEIS" research program [2-4].

Used specimens, that had suffered strength degradation of more than 50% were filled with cement based repair mortar (fc =35 MPa), forming concrete filled composite beams (CFCBs) and were retested, without any other kind of repair.

CFCBs are reported to have demonstrated higher axial load capacity, better ductility performance, larger energy absorption capacity and lower strength degradation than conventional reinforced concrete and steel hollow section columns[6]. This became apparent by the results or the tests achieved by the experiments, as reported below.

2 DESCRIPTION OF TESTS

The experimental setup is the same with the one used for the tests of the initial specimens. It consists of a rigid frame test rig, an actuator and the test frame. The test frame has height 3.40 m and two strong columns in a distance of 1.50m. The specimens are rigidly connected to the columns (Figure 1) via bolts. In order to assure that plastic hinges would form prior to the demounting of the plates, the specimens had small holes near their ends. The general properties of the fuses beams are presented in Table 1. The steel grade of specimens is S700.

Photo 1 Specimens during retrofit.

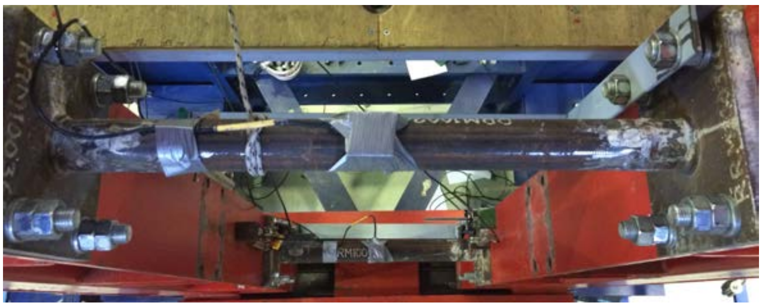


Photo 2 Experimental setup (top view).

Two specimens, initially tested till failure, were filled with cement based repair mortar (fcd =35 MPa), forming concrete filled composite beams (CFCBs) and were retested, without any other kind of repair. The specimens are presented during retrofit (photo 1) and during testing (photo 2).

The initial behaviour of these 2 specimens is analytically reported elsewhere [4], together with another 3 specimens (totally 5), tested simultaneously.

Cross section	Grade	Length (mm)	Yield Stress (MPa)
CHS 76.1*3.2	S700	722	790
CHS 60.3*4.0	S700	722	790

Table 1: Properties of the tested specimens

The specimens were mounted to the test frame, and were subjected to horizontal displacement (δ), that was recorded in accordance to the corresponding force F. (Figure 1).

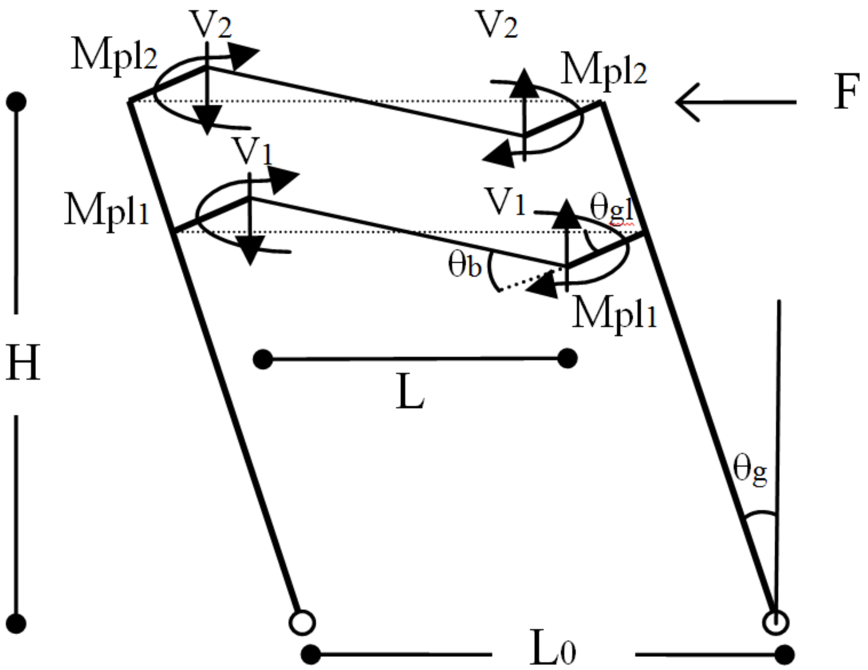
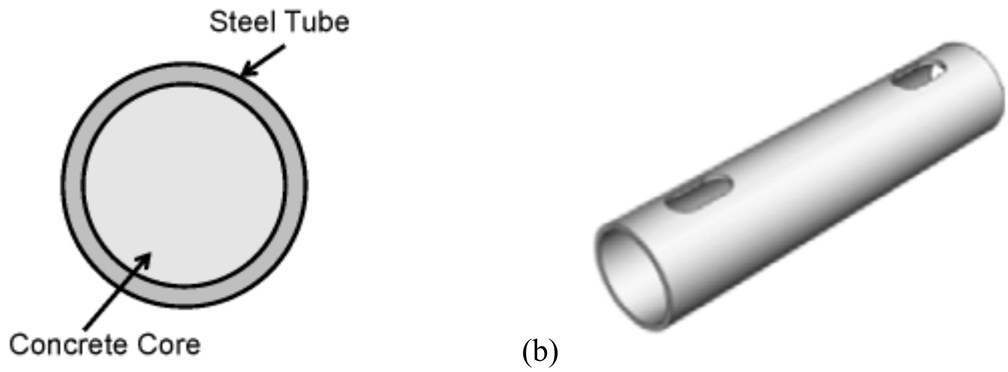


Figure 1: Test layout

3 ANALYTICAL MODEL

Two simple elasto-plastic models of the steel and of the composite beam were used for comparison to the experimental results. These models consist of a simple steel hollow beam for the one and the composition of the same hollow beam with a concrete core that fills the hollow part of the second. The two materials are assumed to be in full contact without interface phenomena (Figure 2(a)). The two existing holes were also modeled (Figure 2(b)). These holes assure that the specimen yields in this section, which is desirable, compared to support damage. Typical stress distribution is calculated; concrete is considered inactive in the case of tension.



(a) (b)

Figure 2: (a) Steel hollow beam section filled with concrete (b) general view

These simplified models are analyzed in monotonic loading. In order to find the stress diagram, the section is divided to stripes parallel to neutral axis. For each stripe the geometrical properties, the bearing capacity and the effective stiffness are calculated via analytical method. The maximum compressive strain of concrete has been estimated to achieve double its nominal value (0.70 %) due to the confinement effectiveness. Axial strain is applied to the model and the forces are subsequently calculated. The moment capacity of the section is calculated under zero axial load. The curvature of the section is:

$$\frac{1}{R} = v'' = \frac{|\varepsilon_{down}| + |\varepsilon_{up}|}{L},$$

where L is the length of the beam and ε are the limit strains.

The displacement of the beams as an integral of the product of the unit and the maximum moment to the flexural rigidity, for different values of strains, is calculated. For each beam and section that was used in the laboratory, a function between force and displacement has been determined. For each tested specimen. The relevant force-displacement diagram according to the analytical model has been produced and is presented in Figure 3(a) both for the 2 repaired specimens and the five initial specimens [4].

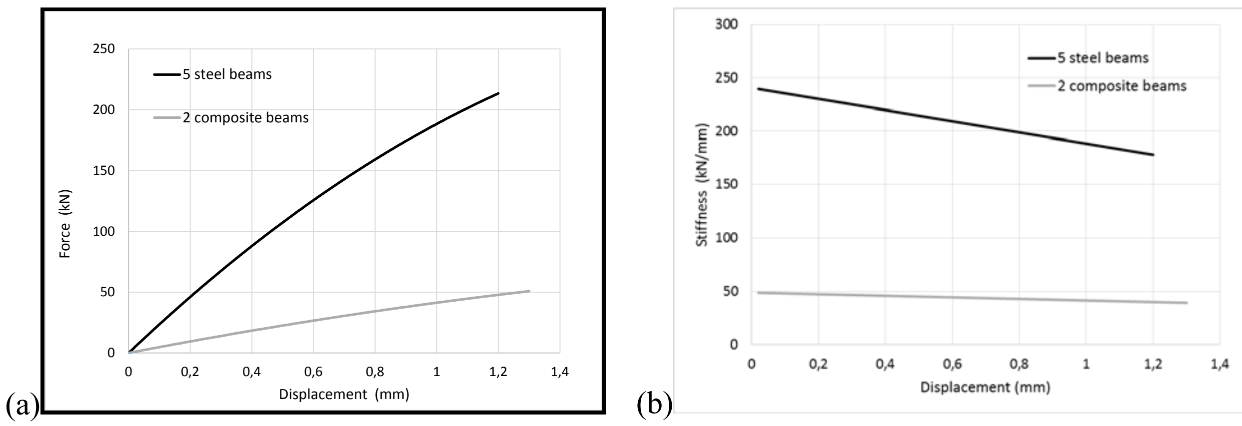


Figure 3: Force displacement diagram and Stiffness Displacement diagram for the 5 steel beams and the 2 composite beams

The difference between the two lines is obvious and is primarily due to the number of the beams. Besides it, there is a difference in stiffness produced in the two cases. The stiffness in Figure 3(b) is calculated as the tangential “Force/Displacement” rate and clearly shows the difference for the two situations. For the initial 5 steel beams this stiffness is higher at the beginning and decreases rapidly until its final value, while for the 2 composite beams the initial stiffness is lower and decreases slightly. The final value of the 2 composite beams stiffness over the value of the 5 steel beams is 0.22 and is used to normalize make the results of the two cases comparative.

4 ANALYSIS OF EXPERIMENTAL RESULTS

The loading, in terms of displacement, applied for the experiments used for the 5 steel beams and with the 2 composite beams described in the prequel, is presented in Figure 4(a). The two loading histories are practically identical; notice that the cyclic displacement loading for the 2 composite beams stopped at 4352sec due to failure while for the simple steel beams reached 5803sec and has not yet failed.

Measured forces for the two different sections, presented in Figure 4(b), are remarkable. For the case of the simple steel hollow section, the forces are symmetrical in tension and compression and they follow the increase in the intensity of the displacements. The forces measured on the composite beam present a totally different response. The response forces are asymmetrical and drastically favor the compression; obviously the concrete fill of the hollow steel section actively participate in the development of this force and is the reason for this asymmetry. The development of the forces with time follow the increase of the displacement intensity until approximately 2500 sec when they start to decrease; this decrease is clear in the case of the composite beam while it seems more subtle in the case of the steel beam. Notice that the force diagram is normalized, i.e. the forces are measured for the combined response of the beams and not each one individually, but a normalization, e.g. with the value 0.22.

This normalization is used also in Figure 4, where the response is presented in terms of force - displacement loops. To be able to compare the two cases, the forces measured for the steel hollow beams are multiplied with 0.22, the coefficient calculated from the stiffness. The final results present vividly the difference due to the initial damage (local buckling) at the region of the holes. It seems this local buckling reduces dramatically the confinement effect.

For the other direction, where concrete remains fully confined, its performance is impressive (Fig.5).

Finally, an equivalent mean stiffness for the first ten loading cycles has been calculated, based on the analytical mode, and was compared to the experiment results. The corresponding values are 48 kN/mm and 16 kN/mm respectively. These values are compatible and, partially, their difference would have been reduced if flexibility of fixation was included in the calculations.

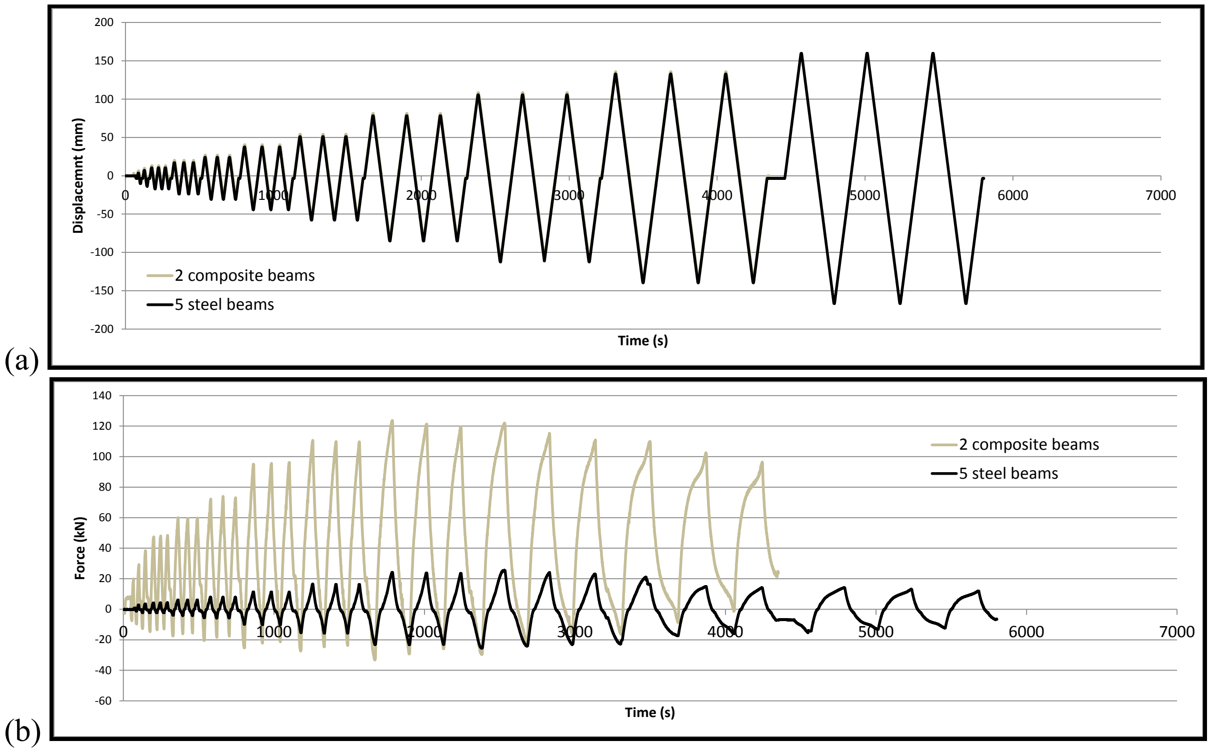


Figure 5: Time histories for the measured (a) displacement and (b) force for the two experiments

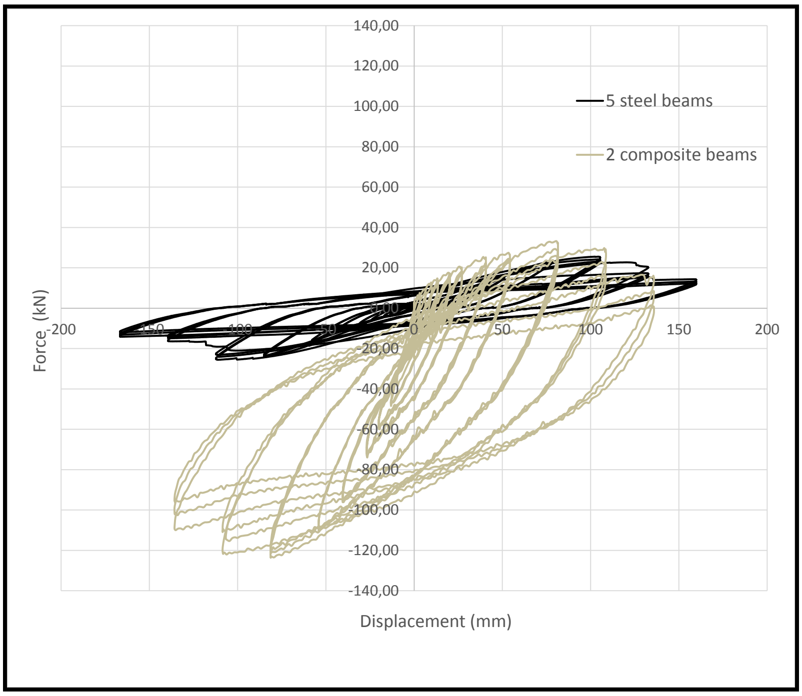


Figure 6: Force displacement loops for the 5 steel beams and the 2 composite beams

3 CONCLUSIONS

- Steel hollow sections, used and damaged as fuses, may retain or increase significantly their initial stiffness and bearing capacity, if they are filled with concrete, and reused.
- Concrete, confined in the tube, can retain extremely high deformations without rupture, due to triaxial behavior.
- Triaxial behavior of conrete is very sensitive to loss of confinement, even locally; this may lead to abrupt reduction of the bearing capacity.
- Steel hollow sections, filled with concrete, appeared to exhibit ductility of the order of μ=10, in terms of displacement.
- Bearing capacity of fuse beam was practically restored to its initial value when the damaged side of the initial specimen was subjected to tension, while it increased to about 5 times its initial value, when the damaged side is subjected to compression.
- Increase of energy dissipation per loading cycle was also remarkable (about 150%).
- The deformation limits that the cement based repair mortar has reached are larger enough than the initially assumed (0,7%).
- It's evident that further research on the subject is needed.

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