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NONLINEAR DYNAMIC RESPONSE OF DISSIPATIVE DEVICES FOR SEISMIC RESISTANT STEEL FRAMES: EXPERIMENTAL BEHAVIOUR AND NUMERICAL SIMULATION

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Abstract. *This study presents the preliminary numerical and experimental results of the project Fuseis carried out with the financial grant of the Research Programme of the Research Fund for Coal and Steel of the European Union (RFSR-CT-2008-00032)), initiated in July 2008 and supposed to end in July 2011, which aims at developing two innovative types of seismic resistant steel frames with dissipative fuses. The numerical model is developed using the commercial software package Perform 3D Nonlinear Analysis and Performance Assessment for 3D Structures by CS&I. The analyses are carried out using inelastic fiber sections for the fuse elements and the composite slab, and elastic steel column elements for the columns.*

1 INTRODUCTION

Steel structures in seismic zones are designed for stiffness, strength and ductility. Stiffness is required for limitation of damage of non-structural elements and reduction of the 2nd order effects. Strength is required for a safe transmission of the acting forces and moments. Ductility under cyclic loading leads to the dissipation of the input seismic energy and results in a reduction of the seismic forces. The demand for strength is therefore closely connected to the provision of ductility. The latter may result in a considerable reduction of the acting seismic forces by a factor of up to 6, according to the European and 12 according to the American Codes.

Obviously, not the entire structure shall exhibit uncontrollable inelastic deformations during a strong earthquake. Such deformations are associated with damage and shall be limited into specific zones, the dissipative zones. For that reason, the elements of the dissipative zones are weaker than their connections and the adjacent members. The latter are designed for higher forces and moments according to capacity design criteria. Table 1 shows an evaluation of the existing conventional structural systems in respect to stiffness and ductility. Strength is not evaluated since it is accepted that all systems, if properly designed, are able to resist the acting action effects. It can be seen that conventional systems have advantages and disadvantages. Moment resisting frames are ductile but usually flexible. Concentric braced frames are stiffer but less ductile due to buckling of braces. The properties of eccentric braced frames are something between the other two types. Table 1, columns 1 to 3, summarizes the properties of conventional steel frames.

	1	2	3	4
	Moment Resisting Frames	Concentric Braced Frames	Eccentric Braced Frames	FUSEIS Frames
Stifness	-	+	0	+
Ductility	+	-	+	+
Reparability	0	-	0	+
Dissipative zones	Beams	Braces	Links	Fuses

Table 1: Stiffness, ductility, reparability properties and dissipative zones of several structural systems

Inelastic deformations may develop not only under seismic loading but also in other design situations in structures exploiting plastic resistances, i.e. in frames designed according to plastic hinge theory. However, such design refers to the ultimate limit state, where the actions are magnified by the relevant safety factors. Under service conditions, inelastic deformations that may result in damage do not generally occur. Inelastic deformations leading to damage are allowed also in accidental design situations (fire, explosions etc.). When such situations actually occur, repair works are needed. However, accidental situations happen very rarely and refer only to individual structures.

Seismic loading represents a special design situation. For normal buildings, structural safety shall be assured for the design earthquake, which corresponds to rare earthquakes with usual return periods of about 500 years. Damage shall be limited for frequent earthquakes with return periods around 50 years. However, the international experience shows that the above fundamental requirements are very often not fulfilled. All over again, earthquakes occur that are much stronger than those for which the design was made. The results are well known: Structural collapses leading to loss of human life and, in much wider range, damages that require repair at high costs. Due to the population increase and the concentration in large cities, it may be stated that the seismic risk and the financial consequences increase rather than reduce over time.

For the population, and the judges, it is difficult to understand that the earthquake which had happened was the *rare* one with a return period of 500 years. This is due to the fact that the Codes rely on instrumental measurements of at most 50 years and historical data that extend over a longer period but cannot be directly transformed into engineering figures. They are therefore based rather on statistical extrapolations of natural hazards. It is observed that after a strong earthquake the region where it happened is often upgraded in the higher seismic zone.

The above descriptions and the experience show that unlike accidental loading, earthquakes lead *frequently* to damages in *large* extent. It is therefore advisable to develop structural systems that are simple to *repair*, i.e. to introduce the *reparability* as a new property. An evaluation of the conventional frames in respect to this property is made in Table 1. It may be seen that conventional frames are not well positioned according to reparability. In moment resisting frames the beams or, more usually, their connections shall be repaired. Both are elements that resist gravity loading and are difficult to repair. The same happens with eccentric braced frames where the links, the short parts of the beams, have to be repaired. In concentric braced frames, it is the braces that shall develop inelastic deformations. Damage is therefore expected in the braces, which are long and heavy elements, difficult to handle and repair.

Furthermore it has to be pointed out that, in reality, “steel structures” rarely exist by themselves (eventually just in the case of industrial buildings). Most often, in the case of high-rise buildings, housing, as well as commercial buildings, the steel beams support r.c. slabs. In this case, damage to the steel members results in damage in the r.c. slabs and in the finishes, so that repair works will be increased together with the related costs.

From other engineering disciplines, e.g. mechanical, electrical and automobile or aircraft engineering, it is well known that the best way of repair is the complete replacement of a damaged part with a new one. Such a strategy could be also envisaged in civil engineering, especially for buildings in seismic areas that are more susceptible to damage for the reasons described above. Like bumpers in cars that absorb the crash energy and are replaced afterwards, innovative devices will be developed that dissipate energy, protect the overall structure and may be dismounted and replaced after a strong earthquake.

The research proposal aims at developing two innovative types of seismic resistant steel frames with dissipative fuses. In case of strong earthquakes, damage will concentrate only in the fuses, which will be exchangeable. Repair work after a strong seismic event, if needed, will be limited only to replacing the fuses.

This study presents the preliminary numerical and experimental results of one of the two types of devices, that can be applied to the beam to column connection of moment resisting frames, as sketched in figure 1.

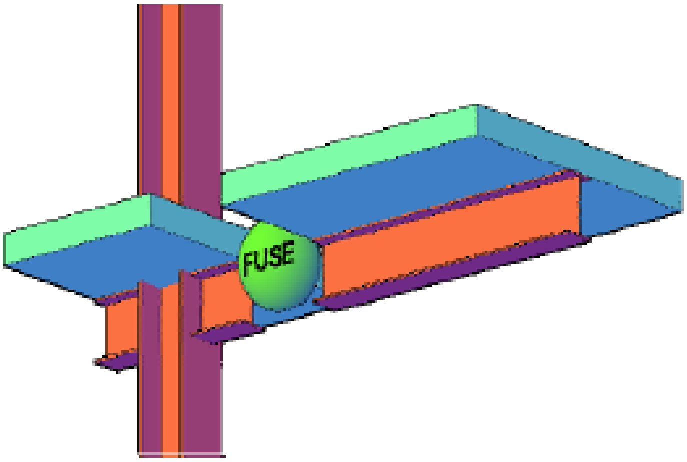

Figure 1: Fuse device placed in a moment resisting composite steel frame

2 FULL SCALE TESTS

A two dimensional composite steel frame with fuse devices has been tested in the structural engineering laboratory of the Politecnico di Milano University. The outline of the frame and its elements can be seen in figure 2.

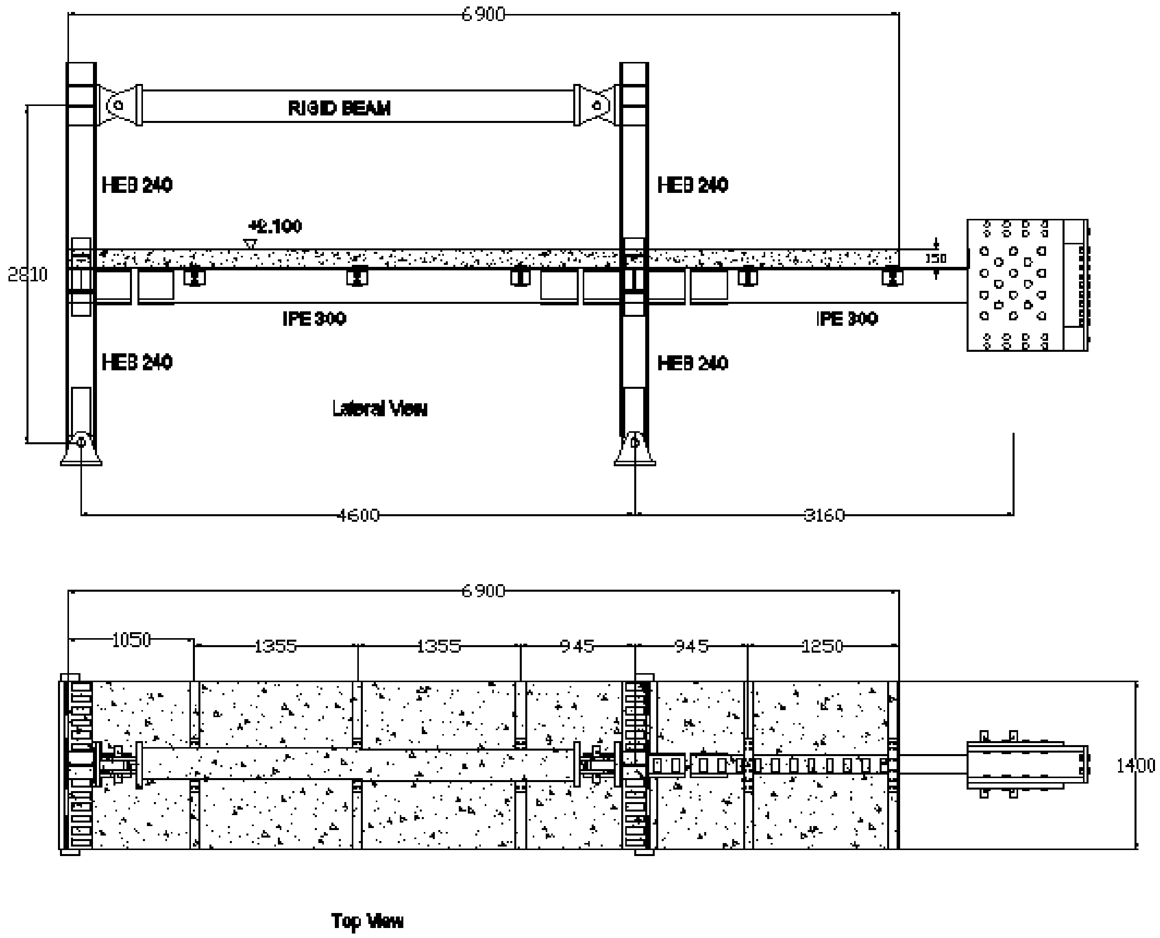

Figure 2 Full Scale Test Frame

A cyclic loading history shown in figure 3 is applied at top joint of the right side column through a load cell. The load is applied in cycles in +x and -x direction. Therefore in each cycle, in the beam and eventually in the fuse element, a positive and negative bending are observed. A maximum deflection of 110 mm (corresponding to 42 mrad in the fuse element) is imposed to the top joint.

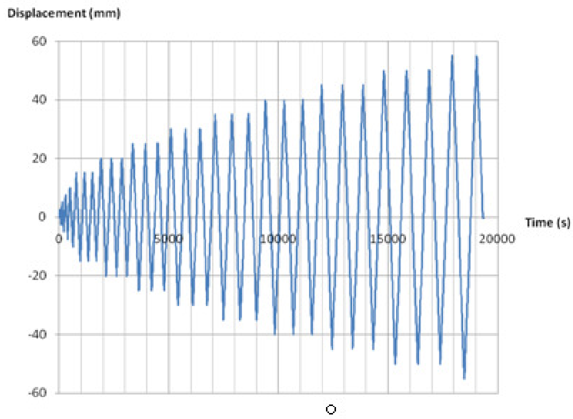

Figure 3 Cyclic loading history applied in the tests

3 NUMERICAL SIMULATION

For the design of the test specimens, a refined numerical model was set-up at Politecnico di Milano, using ABAQUS software. Such a detailed model, however, can be used only for specific research applications, but it is not a feasible model to use for engineering purposes. Therefore, the simplified model hereafter described was set up and calibrated, with the aim of using it for the simulation of multy story frame structures.

The simplified nonlinear model is developed using the commercial software package Perform 3D Nonlinear Analysis and Performance Assessment for 3D Structures by CS&I (Figure 4). The analyses are carried out using inelastic fiber sections for the fuse elements and the composite slab, and elastic steel column elements for the columns.

Figure 4 Perform 3D Nonlinear Analysis Software

A fiber segment is a finite length of constant cross section in a frame compound component. The key aspect of a fiber segment is how it behaves when the fiber section becomes nonlinear, through yield of it several fiber elements. In a beam fiber section, the cross section shape of the element is divided into a number of fibers, and material properties are assigned to each fiber. Each fiber segment is defined by associating it with a fiber cross section and specifying the segment length.

The behavior of a fiber segment is similar to that of a tributary length of beam with a hinge at its midpoint. Such a segment becomes nonlinear only when the hinge becomes nonlinear.

In physical terms, in a fiber segment, the cross section behavior is monitored at only one point, namely the midpoint of the segment. For instance, if a fiber section is made up entirely of steel fibers(i.e., if it models a steel section), the fiber segment yields only when the combination of axial force and bending moment at the midpoint of the segment is large enough to cause a fiber to yield.

The material types that are allowed for the fibers are: Steel material, tension-only material, buckling material and concrete material. [2]

Nonlinear element and material properties are assigned to the composite beams and the fuse elements to observe their contribution to the energy dissipation of the whole frame, during a dynamic lateral loading event. The scope is to attain the plastic behavior only at the fuse elements, and let the columns and beams of the structure behave elastically.

3.1 Properties of Structural Elements

The cross sections and material properties used in the numerical model are the same ones that are used in the full scale test model (Figure 2). HEB240 column elements are chosen as elastic type, considering that the test frame will not be suffer large axial forces. The beams and the fuses are modeled with inelastic fiber segments.

In the frame, there are three different types of beam sections. Main beams are composite steel beams that are composed of an IPE300 steel section, and a reinforced concrete slab of 150 mm thickness. The inelastic fiber section that is used for main beams are seen in the figure 5.

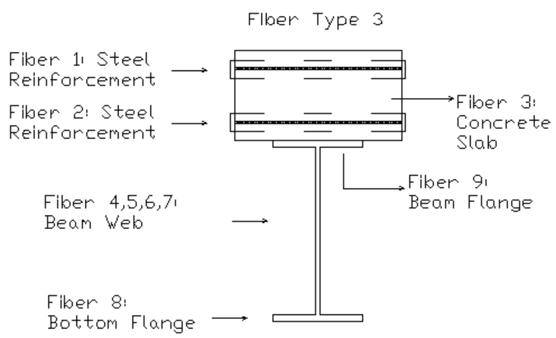

Figure 5 Cross Section Properties of fiber beam element

The short beams located between the fuse parts and the columns are also designed as fiber elements, to represent the behaviour of a composite section which consists of an IPE300 beam, steel plates attached to the flange and the web of the beam, and the concrete slab. The properties of the this beam element can be seen in figure 6.

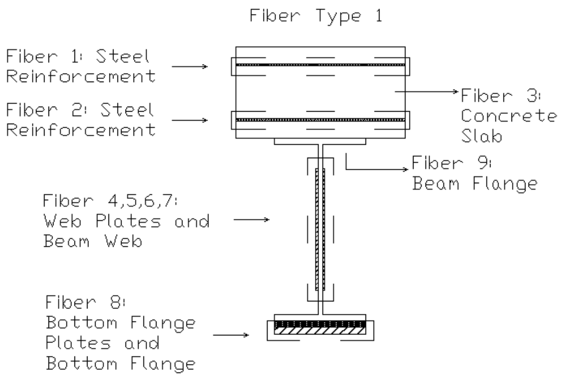

Figure 6 Cross Section Properties of fiber beam element

3.2 Fuse Element

In the model, fuse devices are modeled as short beam segments with fiber cross sections in order to simulate the plastic hinge behaviour. The fiber section used in the model can be seen in the figure 7.

They are modeled with two different fibers:

i) Inelastic steel material, non buckling type, representing the reinforcement of the slab (seismic bars) (Figure 8)

ii) Inelastic steel steel material, buckling type, representing the connection part composed of web and bottom flange plates (Figure 9)

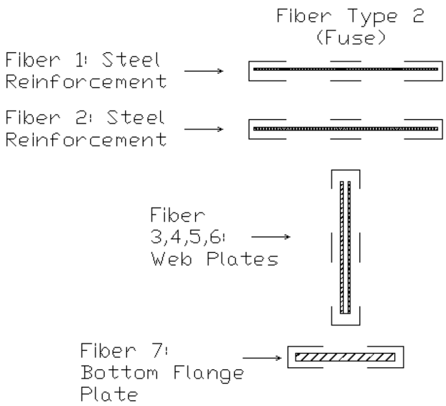

Figure 7 Definition of fibers in the fuse part

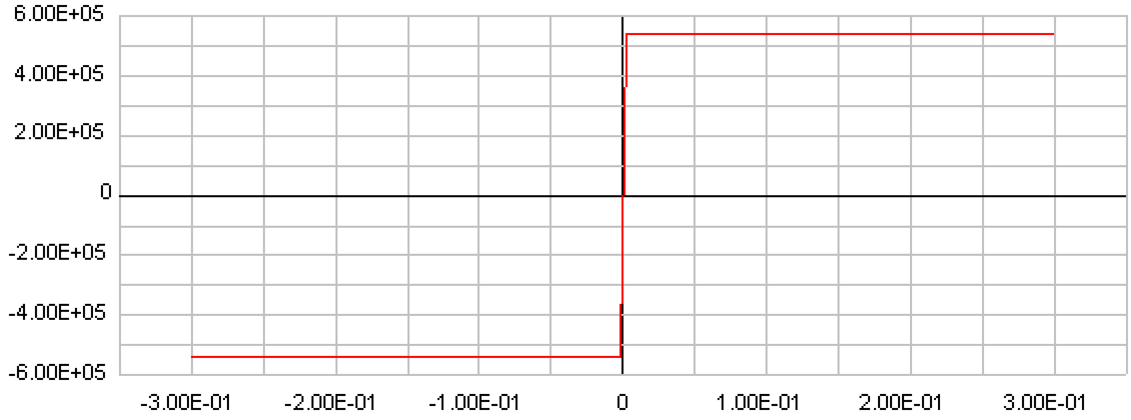

Figure 8 Force-Deformation Relationship of inelastic steel material, non buckling type used for steel reinforcement

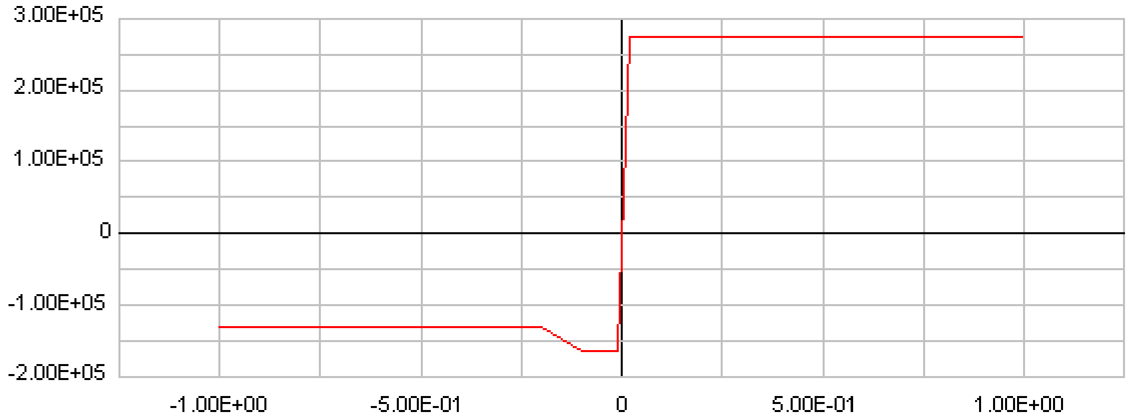

Figure 9 Force-Deformation Relationship of inelastic steel material, buckling type used for web and bottom plates of the fuse devices

The fiber of the steel reinforcement is expected to stay in the elastic range, whereas the fibers of the steel plates connected to the web and the bottom flange are expected to yield and hence dissipate energy during cyclic loading. The locations of the fiber sections can be seen in figure 10.

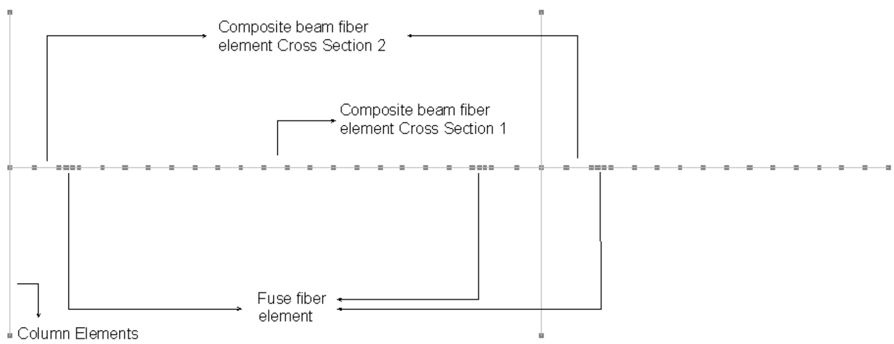

Figure 10 Fiber Segment Scheme of the Frame Model

The output time-force history of the displacement controlled push-over experiment is used as input loading history in the numerical dynamic push-over analysis. Therefore numerical analysis is carried out as force controlled push over analysis (Figure 11).

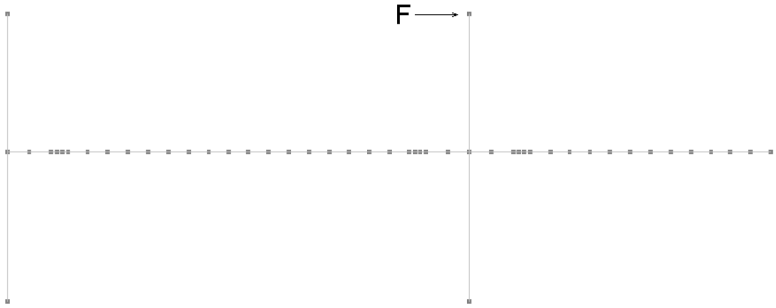

Figure 11 Force controlled push over analysis scheme

The force-time history of the cycling loading case can be seen in figure 12.

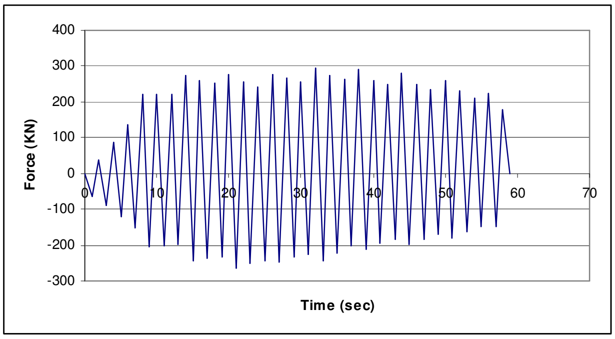

Figure 12 Cyclic loading record used in the model

4 CALIBRATION OF THE NUMERICAL MODEL

The conformity of numerical and experimental results in terms of maximum plastic moment capacity referring to the maximum rotations that the device undergo can be observed in the superposed experimental and numerical global force-displacement plots in the figure 13. The differences in the initial stiffness and amplitude of the hysteresis plots are due to inelastic effects occurring in the connections between the fuse device and the beams, that were not accounted for in the numerical model.

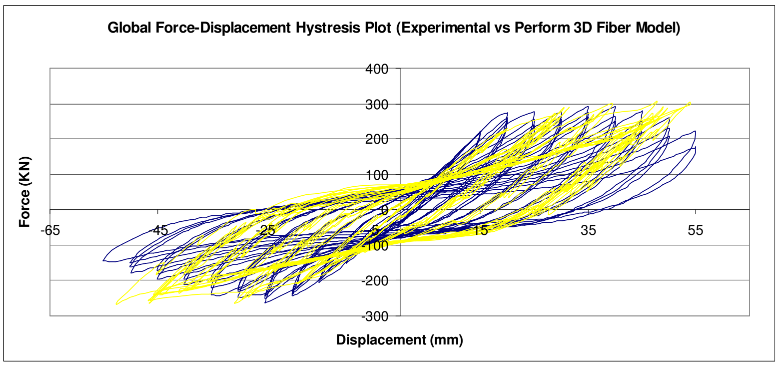

Figure 13 Experimental vs Numerical Moment-Rotation Plots

Within the remaining period of the research project, elaborating the numerical analyses further, the calibration between the analyses and experimental results are going to be improved and necessary design guides to implement the system in practice will be developed.

5 NUMERICAL ANALYSIS OF MULTISTOREY FRAMES WITH FUSES

The expected behavior of a moment resisting multistory frame under lateral loading is shown in figure 14, where a plastic hinge mechanism under collapse load is likely to occur near the beam ends at the floor levels.

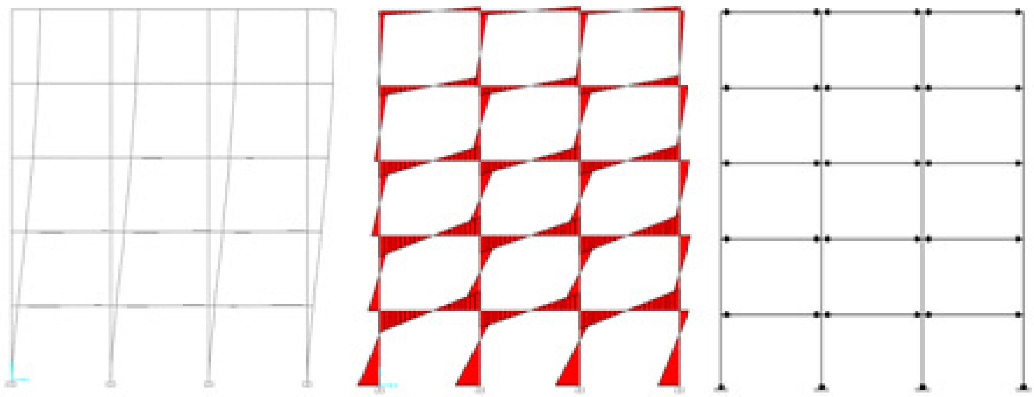

Figure 14 Deformed shape, moment diagram and location of plastic hinges observed under horizontal loading of a 5 storey moment resisting steel structure.

In order to extend the results of the numerical analyses carried for the test structure to multistory building frames and to observe the behaviour of the fuses under horizontal seismic excitations, nonlinear fiber analyses are carried out for two composite steel building frames:

1) A conventional moment resisting composite steel structure building frame
2) A moment resisting composite steel structure building frame having fuse devices, near the end of its beams.

The scope is to observe the behavior of steel building frames using inelastic fiber sections at the parts of the beams where a plastic hinge mechanism is expected to occur, and examine the contribution of fuse devices to the energy dissipation and reduction of earthquake forces in multistory buildings under horizontal earthquake excitations.

The analyses are carried out under the horizontal acceleration time history data of Kobe 1995, Aquila 2009 and Chile 2010 earthquakes. The element types and the cross sections are the same with the ones used in the numerical model of the test frame, which are described in section 2.1.

5.1 Composite Steel Building Frame without Fuses

The composite steel multistory model is analyzed with HEB240 column elements, and a composite slab element that consist an IPE360 steel beam and 150 mm thick reinforced concrete slab.

Under three earthquake excitations, the moment curvature hysteresis plots of composite beam elements are obtained. As can be understood from the moment-curvature diagrams shown in figure 15, the segments of the composite beams where the maximum moments are observed, eventually near beam ends, are plasticized.

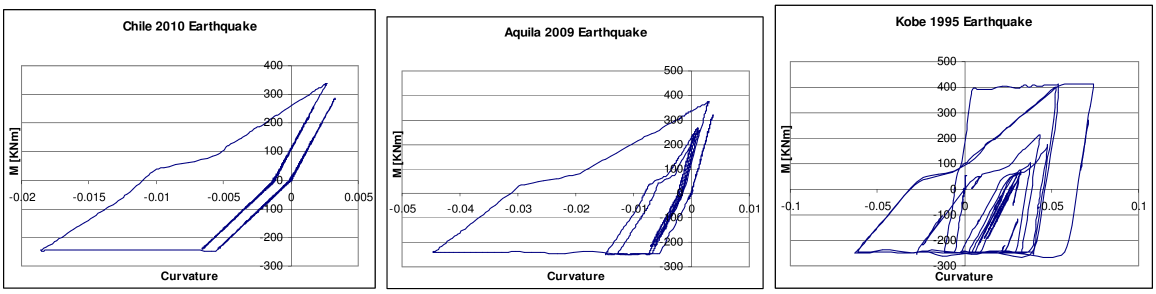

Figure 15 Moment-Curvature diagrams observed in the composite beam under three earthquake excitations

5.2 Composite Steel Building Frame with Fuses

The same building is modeled with placing the fuse devices near the end of the beams, where the plasticization is observed in the previous analysis (Figure 16). The same earthquake excitations are applied to this model as well, and the moment curvature hysteresis plots of composite beam elements and fuses are obtained.

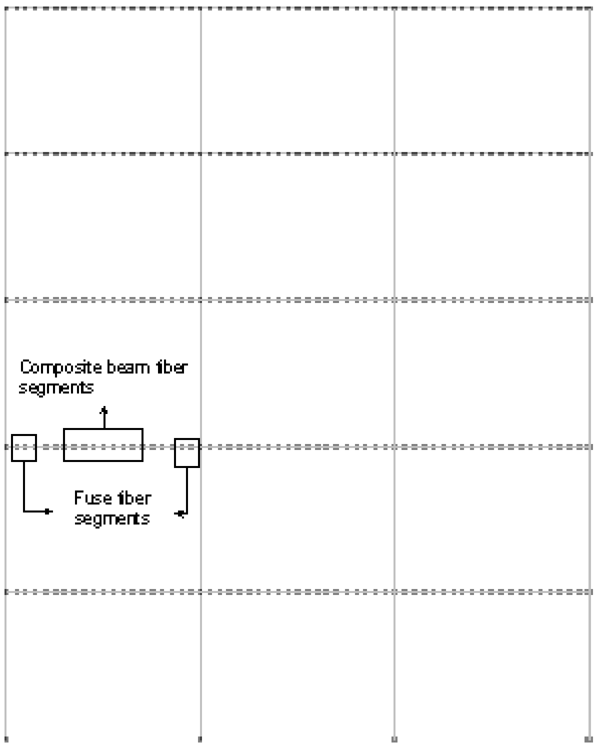

Figure 16 Moment resisting steel building frame model

As expected, the composite beams and columns showed elastic behaviour with no yielding, while the fuse parts yielded and contributed to the energy dissipation. In figure 17 and 18, the moment-curvature diagrams of the composite beams and fuse elements of the structure under lateral loading can be seen respectively.

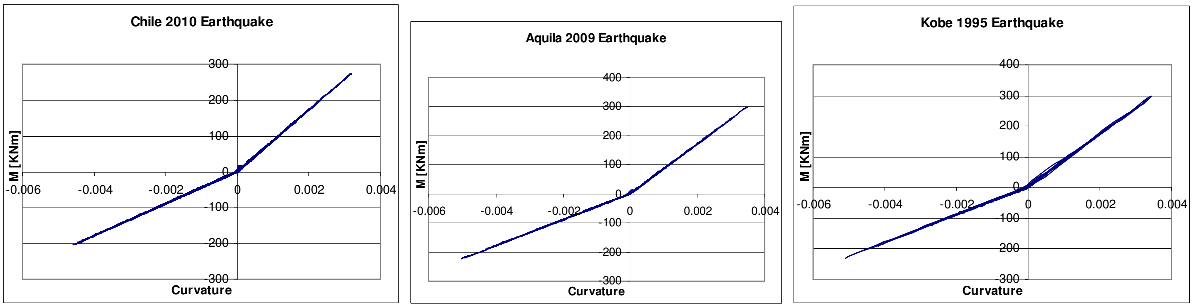

Figure 17 Moment-Curvature diagrams observed in composite slabs under three earthquake excitations

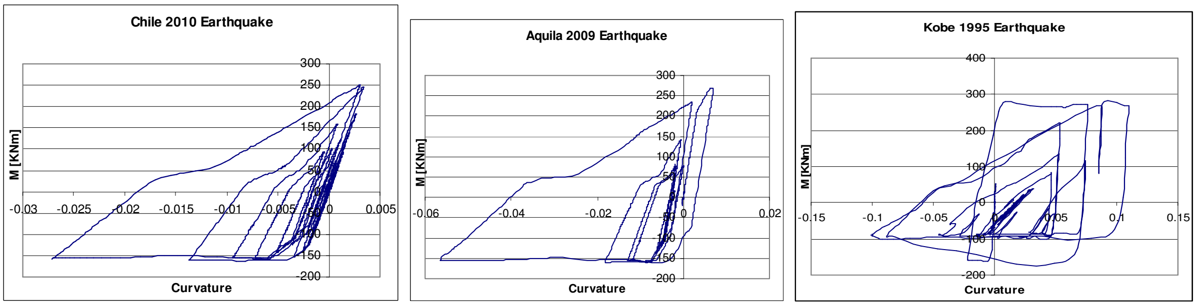

Figure 18 Moment-Curvature diagrams of the fuse devices under three earthquake excitations

From the hysteresis plots, it is seen that the plastic deformations are concentrated only in the fuse elements, whereas the composite beams remain elastic.

5.3 Comparisons between Two Building Models

A comparison between a conventional building model and a building model with fuses is made in terms of base shear forces. In figure 19, the reduction of the maximum base shear forces that take place in the building with fuses can be observed under three different earthquake excitations. Combined with the dissipative behavior of the devices, these results confirm that the fuses have an important effect in reducing the seismic forces transmitted to the structure during strong earthquakes.

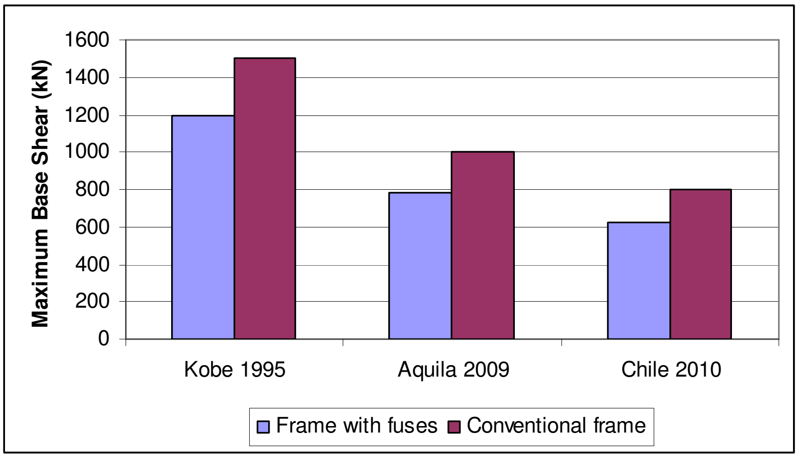

Figure 19 Comparison of maximum base shear forces between conventional and innovative structures

6 CONCLUSIONS

In this study, the preliminary results of the experimental and numerical analyses carried out for one of the two types of innovative fuse devices are presented. The ability of the fuse devices to dissipate energy and reduce the horizontal earthquake forces in steel frames is investigated. The possible damage that the main structural elements of a moment resisting steel frame would suffer during a strong earthquake is aimed to be concentrated in the fuse devices. While in the conventional moment resisting steel frames, the beams and their connections – the elements that resist gravity loading and are difficult to repair- must be repaired after a strong earthquake. In the innovative type seismic resistant steel frames with dissipative fuses, the repair work, if needed, will be limited only to the replacement of the fuses.

From the results of the nonlinear numerical analyses carried out for a simple test structure and a composite steel building frame, it can be concluded that the idea of avoiding the plastic deformations in the main structural elements of a moment resisting building frame can be achieved through concentrating the plastic deformations in "weak" elements which are to be mounted between the beam and column elements of the structure. These comparatively weaker elements, so called fuses, must be stiff enough to let the frame be stable under service loads, and also they must be the principal elements in the structure to show inelastic behaviour and dissipate the energy caused by a strong earthquake.

The numerical analyses carried out for a simple test structure which is loaded in a cyclic manner, showed that among the three elements: composite slab, column, and fuse device, the plastic deformation is observed only in the fuse device, whereas the column and the slab elements remained perfectly elastic. Finally, in order to extend these results for a multistory building frame and to observe the behaviour of the fuses under seismic excitations, a nonlinear fiber analysis is carried out for a two dimensional composite steel building frame consisting steel column elements, composite beam elements and fuse elements, under horizontal acceleration time history data of three different earthquakes. In compatibility with the results of the test structure, also in this case, the plastic deformations are only seen in the fuse devices. Moreover, through the comparison between the numerical analysis results of a conventional steel frame and an innovative type of steel frame with dissipative fuses, it is seen that the base shear forces induced by the strong earthquake motions can be reduced using fuse devices.

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