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EFFECTIVENESS OF ENERGY ABSORBING ELEMENTS IN COMPOSITE STEEL FRAME STRUCTURES

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SUMMARY

Presented in this paper are the basic parameters confirming the advantage of the application of seismic energy absorbing elements of steel or composite steel frame structures. The analysis of the effectiveness of such systems has been carried out on the basis of original applied investigations for development of energy absprbing elements. The efficiency test, which prove the justification of the application of such elements, that in addition of increase in the structural damping capacity increase the lateral force as well is shown on the case of a five-storey frame. This example has shown that the saving in material for the main structural system is as much as 20 percent.

INTRODUCTION

Recently, intensive investigations in the field of earthquake resistant design and construction of buildings applying the composite steel frame structural system have been carried out at the Institute of Earthquake Engineering and Engineering Seismology, University "Kiril and Metodij" in Skopje. The composite structural elements (columns) are made of hollow square cross-section steel profiles infilled with concrete. These systems have high load bearing capacity to sustain gravity loads, however, for the lateral loads, such as the seismic forces, characterized by high moments and shear forces, considerable increase of the elements cross-section is required, which significantly increases the cost. Therefore, in the development of the composite elements structural system it is necessary to apply structural elements which will have a double role. First, to increase the energy absorbing capacity of the composite elements structure, and second, to increase its lateral rigidity. To meet these goals, various solutions have been considered leading to the final investigations focused on determination of the shape and the mechanism of connecting the energy absorbing elements to the basis of the structural system.

Applying this concept a structural system has been developed for construction of buildings with composite columns, flat slabs and energy absorbing elements having relatively high flexibility of application. Depending on the seismic excitation level and the limitations of the steel profile producer the gamma of the application of this system has been determined. In other words, it can be applied for buildings as high as twelve storeys (because of the limitations of the steel profiles producer) and for plan geometries of 7.2 x 7.2 m basic modulus or combinations of half a modulus.

The general efficiency of the system, as well as the efficiency of the energy absorbing elements are always compared to structures of the same geometry constructed by a classical method. Presented in this paper are the basic characteristics of the energy absorbing elements and the comparative value of a five storey building structure constructed with and without energy absorbing elements, since the efficiency of this system increases with increase in the height of the structure.

TESTING PROGRAM

A five storey building has been designed with steel energy absorbing elements built in two spans out of four over the whole height of the building in both orthogonal directions. The prefabricated frame columns are made of 260x260x7 hollow steel profiles filled-in with concrete, while the floor structures are reinforced concrete slabs, 20 cm in thickness (Figs 1 and 2). Quasi-static testing is carried out on a frame with and without energy absorbing elements selected from this structure. Dynamic analysis is carried out for the designed building according to the Yugoslav Codes for Aseismic Design and Construction, and on the basis of this analysis the loading schedule for the tested frames has been determined.

The tested models have a floor height of H = 3.0 m and a span of L = 3.6 meters (Figs 3 and 4). The I14 profile beams are bolt-connected to the columns. This profile is embedded in the 20 cm thick floor structure between the Ø 8/10 cm grid reinforcement, placed in the lower zone, and Ø 12/11 cm grid reinforcement, in the upper zone. The compression strength of the floor structure concrete is 30MPa, while the width of the slab is 90 cm (Fig. 2). The energy absorbing elements are made of 120x120x5 hollow profiles. The energy absorbing elements in the internal portion of the frame span are of rectangular shape with dimensions 108x95 cm and it is connected to four profiles, 107 cm in length, in the direction of the external angles diagonal. All the joints of the energy absorbing elements are welded. All the steel profiles and energy absorbing elements are made of steel with yield point of 240 MPa (Fig. 4).

The hydraulic jacks 1 and 2 (joint A), through which gravity load is applied, are fixed to the upper ends of the columns, and their lower ends are hinge connected (joint B) to supporters 1 and 2. Cyclic horizontal forces is applied through the upper end slab (joint C). The models are tested in horizontal position. After applying a constant axial force of 215 kN, through the hydraulic jacks 1 and 2, cyclic horizontal excitation was applied by increments of 10 kN through the hydraulic jack 3. During the test the displacement in horizontal excitation direction was used as a leading value.

Each model was instrumented with 50 measuring points, which enabled to obtain axial forces, cyclic horizontal force, absolute and relative displacement of the frame and energy absorption, stresses in the steel profiles as well as stresses in the floor structure reinforcement. LVDT and clip gages were used to measure the displacements while for measuring the strains strain gages were used. Automatic data acquisition was provided simultaneously with the load excitation process. Data processing was carrying out using a PDP 11/45 computer system with an A-D convertor, and all the experimental data were stored on a memory unit for further processing. The processing was controlled interactively by a video-terminal, which enabled following of all the used channels. An x-y plotter was used for direct control of the main quantities (force and displacement) of the actuator, which provided the hysteretic relationship of Q-δ in a previously given scale.

EXPERIMENTAL RESULTS

The inelastic behaviour of the frames can be explained the best by the hysteretic diagrams of the horizontal force and the displacement at the upper slab level of the model (Fig. 6). Developing of cracks in the upper and lower slab of the model, due to exceeding the tensile stresses, was the first sign for inelastic behaviour of the model.

The characteristic yielding point of the model with energy absorbing elements is determined based on the horizontal force-displacement hysteretic relationship at the occurrence of considerable decrease in the rigidity of the model. After yielding, the horizontal force continues to increase and reaches its maximum value at the horizontal displacement of 20 mm, when local buckling occurs at the ends of the horizontal parts of the rectangular in the center of the steel absorbing elements (Fig. 6). In the final phase of the test the horizontal displacement increases up to 32 mm with considerable decrease in the horizontal force and the rigidity of the model. The cracks in the steel energy absorbing elements increase, but do not cause their breakage. The yielding strength is estimated as the mean value of the horizontal force in both loading directions, and it was 190 kN. Initial inaccuracy in the frame geometry causes different horizontal load in positive and negative loading direction.

After the yielding state the horizontal force continues to increase reaching a mean maximum value of 225 kN at a horizontal displacement of 20 mm. By increasing the horizontal displacement up to 28 mm the strength capacity of the models decreased up to 170 kN, which is 75% of the maximum attained strength capacity. The force-displacement relationship for the tested model without energy absorbing elements is shown in Fig. 5. It can be seen that the model begins to behave in nonlinear range for a displacement of 25 mm corresponding to elastic force of 20.0 kN. During the whole tested period of the models the columns remained in elastic range.

It has been previously mentioned that yield displacement of the models with energy absorbing elements is determined on the basis of the hysteretic diagrams when considerable decrease in lateral rigidity of the model occurs. For the yield displacement determined in this way the displacement ductility is $D\delta = 3.30$. The lateral displacement for this ductility is 28 mm, when the lateral force decreases to 75% of the maximum force applied during the testing. This lateral displacement state can be completely accepted, considering the strength capacity of the models at maximum displacement.

One of the basic aspects which has been studied is the capacity of the models for absorbing and dissipated energy. The dissipated energy is determined from the horizontal force-horizontal displacement hysteretic diagrams. To enable comparison of the dissipated energy, it is normalized by the mean horizontal displacement in the same cycle. In Fig. 7 it is shown the normalized dissipated energy in nonlinear range of behaviour. It can be noticed that the most part of the energy is dissipated at the horizontal displacement between 20 mm and 30 mm. The maximum dissipated energy per cycle is 420 kN, which can be compared with the dissipated energy of three-storey reinforced concrete wall models with a total height of 290 cm and cross-section dimensions of 7x153 cm |DEM1E|.

To evaluate the difference in the behaviour of the frames with increase in inelastic displacement, the efficiency indices of energy dissipation are plotted in function of the accumulated dissipated energy, normalized by the energy accumulated at yielding per a semi-cycle, i.e. $\Sigma Ei/(0.5\ Qy.\delta y)$. On the basis of the diagram in Fig. 8, it can be concluded that the model with energy absorbing elements has a high efficiency level for energy dissipation, ranging between 80% to 90%, compared to an idealized elastoplastic structure.

COMPARISON ANALYSIS OF THE CONSIDERED STRUCTURAL SYSTEM

The comparative analysis of the considered structural system of composite steel columns and energy absorbing elements has been carried out from the aspect of the quantity of built-in material for the structure and the required construction time. Comparisons are made with respect to a structure of the same geometry constructed of reinforced concrete or steel composite columns without energy absorbing elements. On the basis of the comparative analysis with respect to a reinforced concrete building the obtained results show an average saving in material of 14% and decrease in construction time of 48 % which is due to the possibility for the considered system to be industrially produced.

The comparative analysis aimed at determination of the effectiveness of the structural system with energy absorbing elements with respect to that one without such elements show also interesting results. Although it is well known that the efficiency of bracing elements has a higher influence in the case of buildings with more storeys, the lower, five storeys limit has been taken as possible application. Namely, a five storey four span frame with and without energy absorbing elements has been designed according to the Yugoslav Code for the same seismic effects and gravity load (Fig. 10). The frame without energy absorbing elements has the same geometry as the one in Fig. 10 except that the first and the fourth span are identical with second and the third one. Comparison of the absolute (Fig. 9) and the relative storey displacements, the required ductility and the development of plastic hinges (Fig. 10) is made. For all the compared mechanical properties the frame with energy absorbing elements has an advantage with respect to the frame without such elements. The limited space of this paper does not allow presentation of all the obtained results.

The comparison from the aspect of the cost in terms of the quantity of construction steel for the considered five storey frame has shown that the frame with energy absorbing elements, in addition of having an increased damping capacity of the structure and considerable change in the lateral rigidity, requires smaller quantity of steel for about as much as 20% than the frame without energy absorbing elements.

CONCLUSIONS

If the energy absorbing elements in steel frame or composite steel frame structures are designed to increase the lateral rigidity of the frames, influence considerably their dynamic behaviour. It has been concluded that besides the significant increase in the hysteretic damping of the structure the frames with energy absorbing elements decrease required quantity of steel reinforcement for about 20%, compared to frames without such elements.

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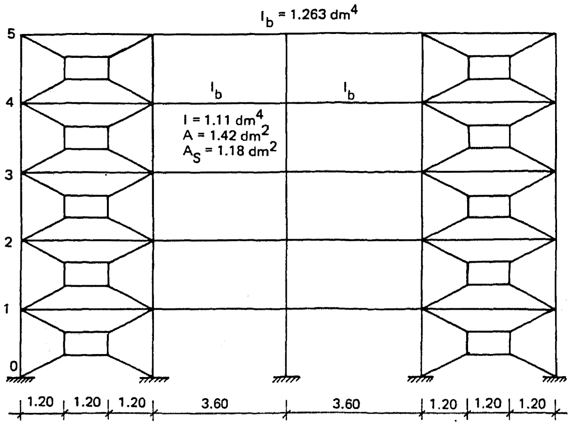

Fig. 1. Frame with energy absorbing elements

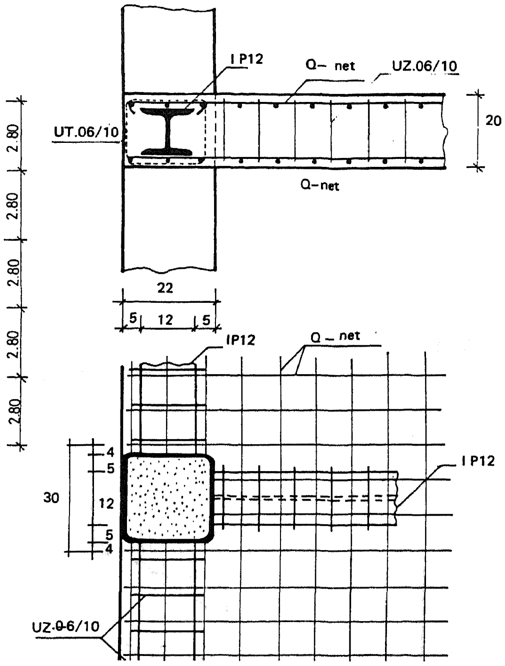

Fig. 2. Connection between floor slab and external column

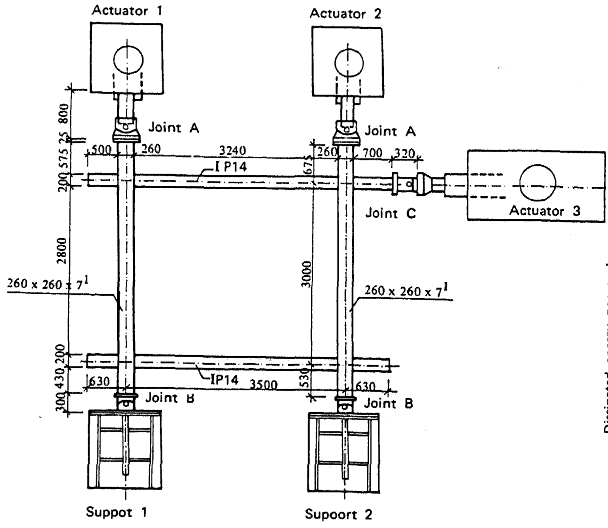

Fig. 3. Frame model without energy absorbing elements tested under combined axial load and cyclic lateral loading

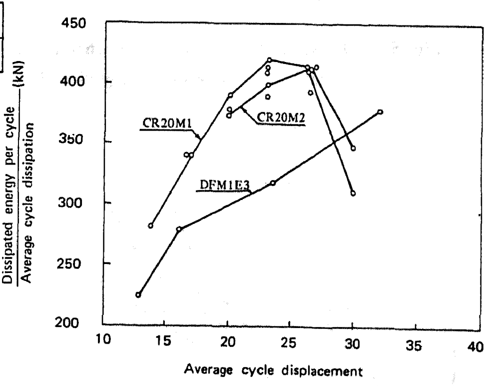

Fig. 7. Normalized dissipated energy

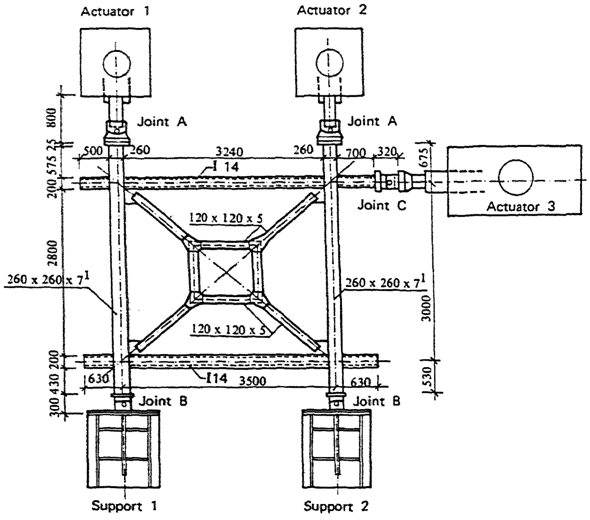

Fig. 4. Frame model with energy absorbing elements tested under combined axial load and cyclic lateral loading

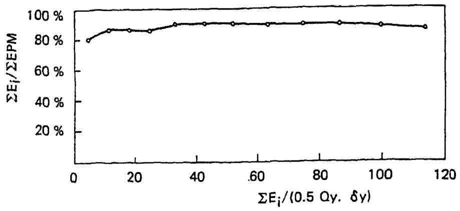

Fig. 8. Energy dissipation efficiency

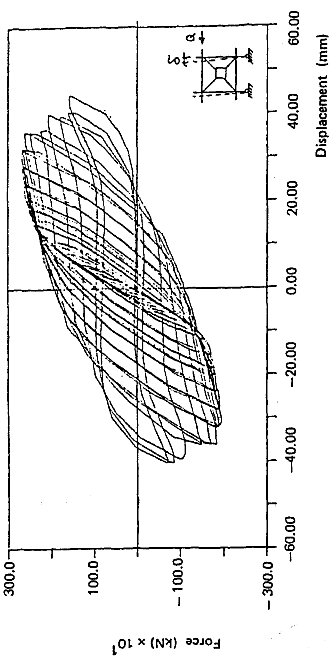

Fig. 6. Load - deformation relationship for a frame model No. 1 with energy absorbing elements

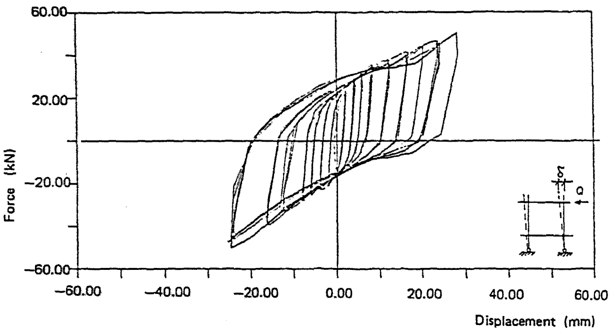

Fig. 5. Load - deformation relationship for frame model No. 1 without energy absorbing elements

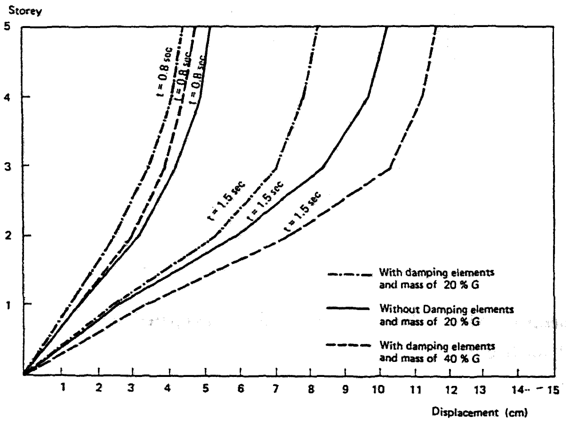

Fig. 9. Absolute storey displacement

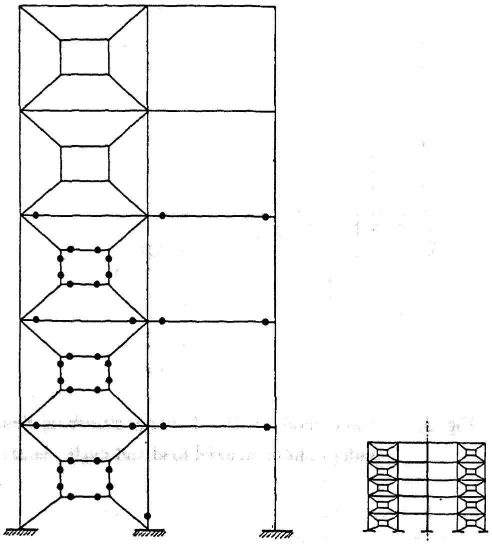

Fig. 10. Development of plastic hinges and frame energy absorbing elements