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DEVELOPMENT OF A PASSIVE CONTROL SYSTEM FOR STEEL FRAME STRUCTURES

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ABSTRACT

The developed passive control system disposable elements and friction damping mechanism-DEFD contributes to increase in the initial stiffness and damping capabilities of the structure. It introduces additional defense lines in the structure exposed to earthquakes: friction mechanism with limited slip-slotted bolted connections (SBC); disposable elements-central rectangular ring fixed at the intersection of the braces and the braces themselves. Furthermore, this system introduces hysteretic damping at low to moderate seismic excitation into the structure, by activating of friction mechanism. It shows significant increasing of the damping at low intensity earthquakes and generate hysteretic damping for the initial, usually lower, amplitudes for the strong earthquake effect. This system enables controlled deformation of the structure with high damping capacity.

KEYWORDS

Steel frames structures, seismic excitation, disposable elements, slotted bolted connections, energy absorption, friction damping.

INTRODUCTION

The intensive investigations in the field of passive control of structures performed in the world most famous research centers, during the last two decades, resulted in a large number of different technological solutions, part of which have been already applied to full scale structures.

Up to now, have been developed different types of passive control systems for steel frames structures, as eccentric diagonals, friction dampers, disposable elements-knee bracing, ADAS system (Whittaker at al., 1989) and many others. Common feature, for all passive control systems, is that the structure should be provided by elements capable to absorb as much as of input energy during earthquake ground motion. By this way main structure would remain undamaged, or slightly damage easily reparable.

The objectives of the investigations which have been carried out at the Institute of Earthquake Engineering and Engineering Seismology in Skopje are to upgrade earthquake resistant safety of the structure with practical application of the solutions which have proved to be efficient and less costly.

The proposed passive control is an attempt to further develop the concept of the implementation of disposable elements (DE) as control devices in dual-system frames (Braced Moment Resisting Frame). The developed passive control system DEFD is based both on the knowledge gathered from numerous investigations, carried out in this field in the past at research centers in the world, as well as based on the research experience gathered by investigation at the Institute in the period 1985 - 1994.

DEFD SYSTEM - GENERAL INFORMATION

Although this system (Fig.1) represents an extension of the system for passive control with elements for increasing the stiffness and damping, developed at IZIIS in the period 1985 - 1987, still represents a new and original solution by which hysteretic damping under low seismic effects is introduced for the first time. This is achieved by introducing a friction mechanism with a limited slip (SBC) at the joints of the frame structure. The activation of this mechanism under relatively moderate excitations introduces hysteretic damping in the structure. This is done to increase the damping under low intensity earthquakes and to generate hysteretic damping for the initial, usually smaller amplitudes of motion under strong earthquakes.

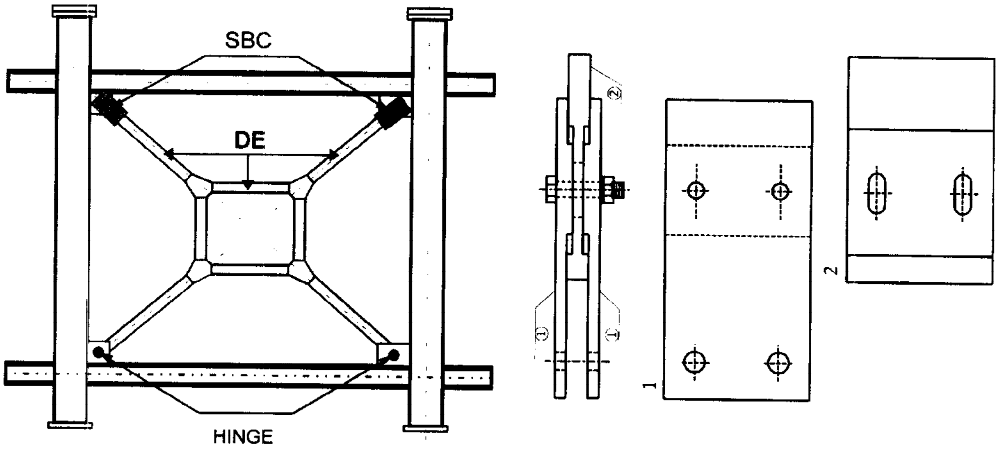

Fig.1. Developed Passive Control System - DEFD

The friction mechanism, SBC consists of three plates. The central plate is connected to the top and the lower plate by means of two bolts, in the form of a sandwich. The upper and the lower plate have round openings with standard diameter in respect to the used bolts, whereas elongated openings are drilled through the central plate. When the applied force exceeds the friction force between the plates, which is achieved by introducing prestressing force in the bolts, the central plate starts to slip in respect to the upper and the lower ones. This process is iterated also in the opposite direction because of the cyclic nature of the applied force. During this process, an energy dissipation takes place for the purpose of sustaining the friction forces occurring between the slipping areas.

When the slip tolerance of the plates is over, the additional forces activate the disposable elements (Fig. 1) consisting of the central rectangular ring and the diagonals whereat additional energy dissipation takes place through their plastic deformation.

EXPERIMENTAL PROGRAMME

Static and dynamic tests were carried out on SBC. The objective of these tests was to determine the static and dynamic friction coefficient between the sliding surfaces, which also means definition of the magnitude of the force causing plate sliding.

Dynamic and quasi-static tests were carried out on isolated part of DEFD system, consisting of two (one during quasi-static tests) friction devices SBC, and disposable elements - two braces and central rectangular ring fixed in the intersection of the braces . The objectives of these tests were to determine the influence of the friction devices to the disposable elements and to estimate the capability for absorbing energy of the passive control system DEFD.

All test were carried out at the Dynamic Testing Laboratory of IZIIS, using dynamic actuator to generate harmonic excitation, during dynamic testing, and equipment for quasi-static testing during corresponding tests.

Results

The experimentally obtained static friction coefficient, $\mu=0.44-0.49$, is quite a good coincidence with the one recommended in the effective steel Codes, which for such a way of finishing of sliding surfaces is 0.5. The sliding surfaces were sand blustered. Dynamic friction coefficient between sliding surfaces of SBC, obtained through several tests imposing sinusoidal displacement time history with 1, 2 and 5 Hz, is around 0.33 (Fig 2.).

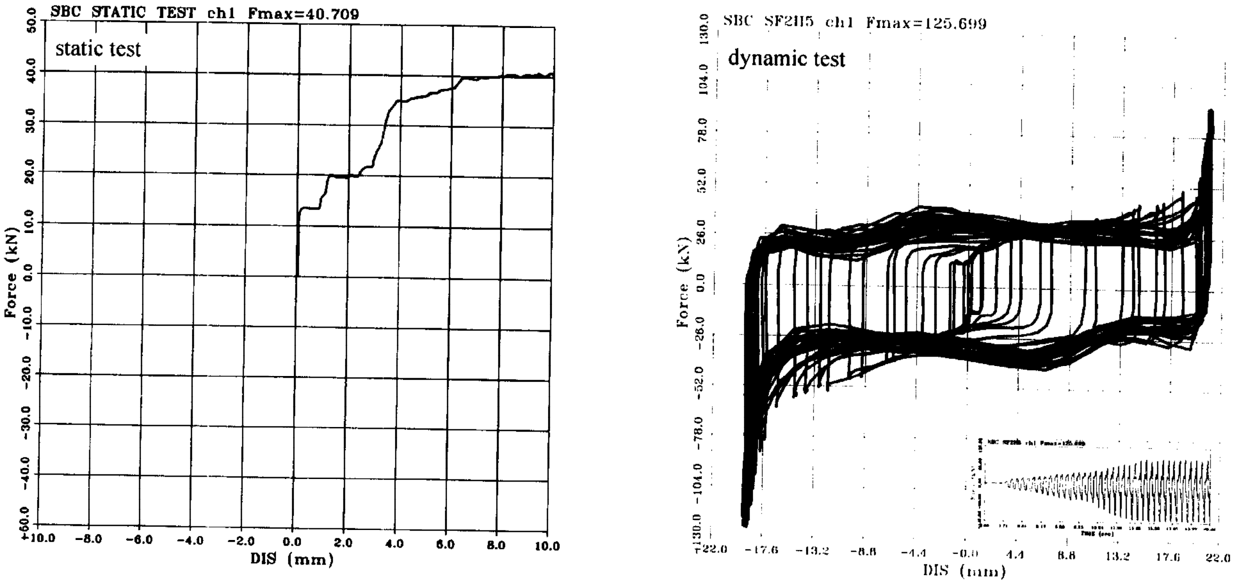

Fig. 2. P-Δ diagrams - static and dynamic tests of SBC

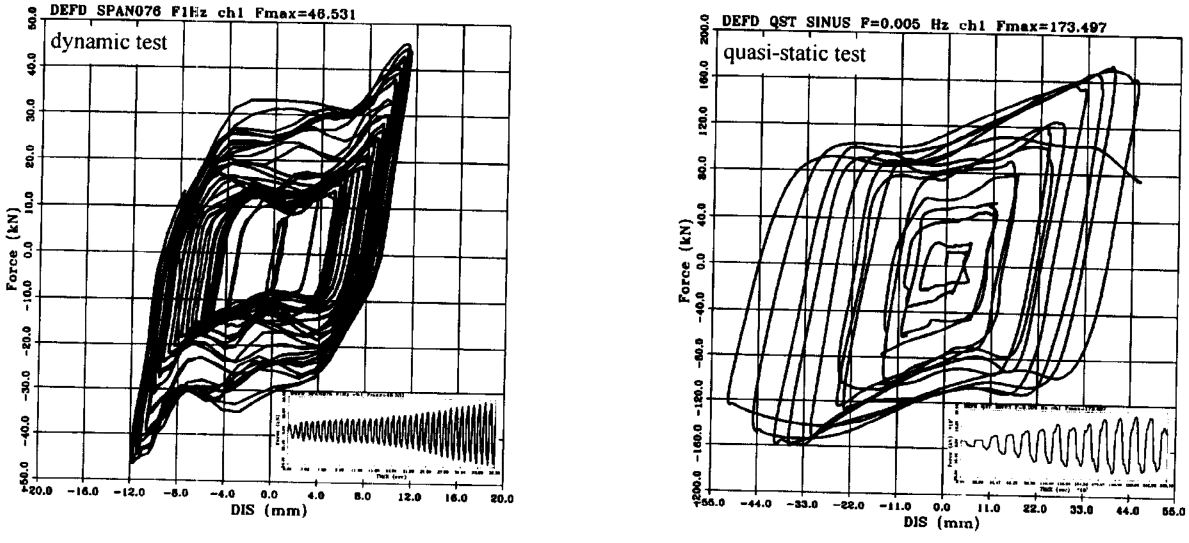

Fig. 3. Global P-Δ diagrams - dynamic and quasi-static tests of DEFD

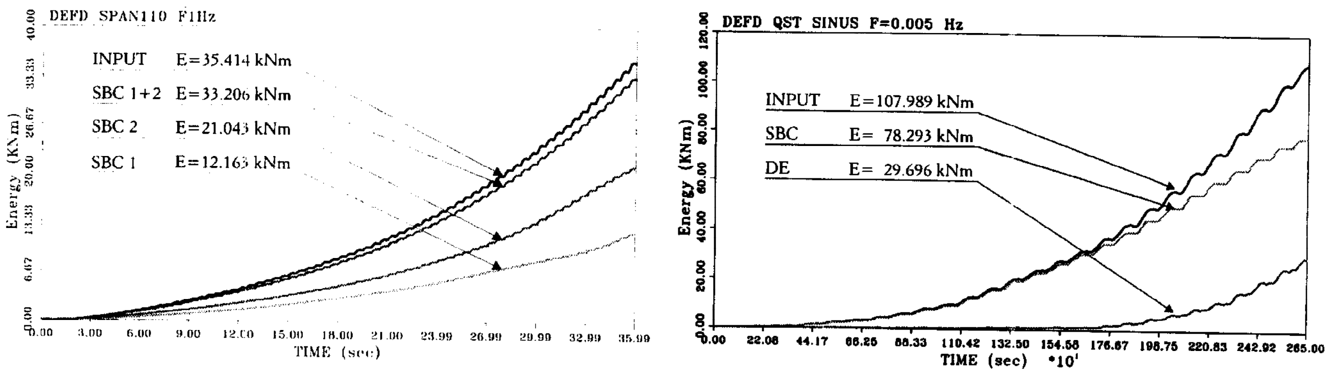

Fig. 4. Input energy and dissipated energy time histories
dynamic and quasi-static tests of DEFD

Results obtained from experimental testing(Fig.3 and 4) of isolated DEFD system indicates that friction mechanism with limited slip, SBC, has great influence on the response of the passive control system.

While disposable elements are in linear range, the energy is dissipated by the friction mechanism. After reaching the yielding point of the material (structural steel σy=240 MPa) in the disposable elements, due to plastic deformation of the central ring, additional part of input energy is dissipated (Fig. 4).

The behaviuor of SBC is highly affected by adhesive and abrasive wear, which occurred during sliding of friction mechanism, which results in adverse conditions for the maintenance of stabile frictional force between sliding surfaces of SBC, during slippage. Those kinds of wear has to be eliminated completely, and if it is not possible to minimize them as much as possible. It could be done by utilizing steel materials with high hardness, for the plates of friction mechanism, different way of finishing sliding surfaces, by introducing shims of steel like materials or alloys between sliding surfaces.

MATHEMATICAL MODELING

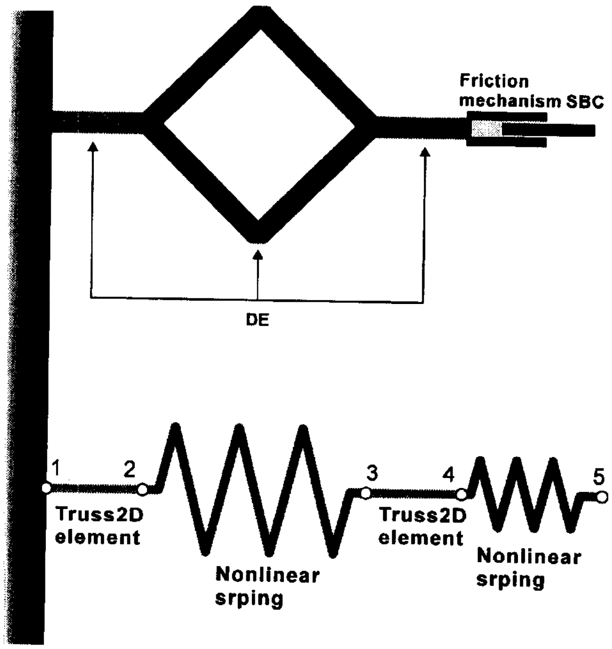

Fig. 5. Mathematical model for nonlinear response analysis

Based on experimental results, obtained by quasi-static testing of isolated part of DEFD system, mathematical model for nonlinear behaviour of tested elements is formulated. Mathematical model (Fig. 5.) is consisting of four elements, two linear truss elements representing diagonals, and two nonlinear springs, representing central rectangular frame and friction mechanism respectively. For each of the nonlinear elements P-Δ relationships are defined regarding the introduced degrees of freedom of the elements. Thus, for the nonlinear spring, which is used to simulate the nonlinear bahaviour of the central rectangular ring, poly-linear hysteretic model is used, while for the other nonlinear spring (friction mechanism) bi-linear (rigid-perfectly plastic) model is used.

Proposed solution should not to be accepted as final, but as one of possible approaches in solving of the problem, and as illustration for applying experimental results in formulation of model for nonlinear analysis.

Matrix dynamic equation of motion of MDOF system in classical dynamics is given as:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=[E]\{f(t)\} \tag{1}$$

while for controlled structures has the form:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=[D]\{u(t)\}+[E]\{f(t)\} \tag{2}$$

where:

$\{f(t)\}$ - voector of external forces

$\{u(t)\}$ - vector of control forces

$[D]$, $[E]$ - location matrices for control and external forces

In case of passive controlled structures, such as those with DEFD passive control systems, assuming that control force is linear function of displacement and velocity vector the control force can be obtained as:

$$\{u(t)\}=-\left([C_1]\{\dot{x}(t)\}+[K_1]\{x(t)\}\right) \tag{3}$$

where:

$[C_1]$, $[K_1]$ - control operators

With replacement of Eq.3 in Eq.2, the final form of dynamic equation of motion of MDOF system with DEFD passive control system is obtained:

$$[M]\{\ddot{x}(t)\}+\left([C]+[D][C_1]\right)\{\dot{x}(t)\}+\left([K]+[D][K_1]\right)\{x(t)\}=[E]\{f(t)\} \tag{4}$$

Comparing the Eq. 1 and Eq. 4, it can be seen that the effect of incorporating of passive control systems DEFD is to modify the structural parameters (stiffness and damping) in a such way that the structure to respond more favourable on external excitations.

DISCUSSION OF THE RESULTS

From the review of experience gathered from the investigations of passive control systems that have been performed throughout the world for the last two decades, as well as on the basis of knowledge gained from the investigations performed at IZIIS, it may be pointed out that the passive control systems represent a significant improvement of the methodology for design of seismically resistant structures and a concept which can practically be applied immediately in design and construction of high-rise frame structural systems.

Although each of the passive control systems has its own flaws, these solutions still represent a step forward in comparison with the traditionally designed structures. Their role is either to increase the general safety of structural systems exposed to strong earthquake and reduce damages under moderate effects, or concentrate damages into elements that can easily be repaired or replaced by new ones. The developed passive control system DEFD integrates all these positive effects.

Using this system with friction mechanism with limited slip ,DEFD, the frame structure possesses several lines of defense.

The initial stiffness of the DEFD system is equal to the conventional DE system. It means that for low input force levels - service loads - the response of both the main structures and the control system remains elastic.

When the force in the brace exceeds the predetermined slip force S_o, during a minor-to-moderate earthquake, the friction mechanism is activated. At this stage both the main frame and the disposable elements are still elastic.

Compared to both the Friction Damped Braced Frames (FDBF) and the conventional DE system, DEFD system is somewhat "softer". But, for the first time it introduces a considerable energy dissipation at low excitation levels, without any damage of the structural elements. Due to the large slip forces, the friction damping mechanics of the FDBF system can be not activated in this phase of the response, which means that its energy dissipation is poor. At this stage, the conventional Disposable Elements Braced Frames system is either in elastic (without any hysteretic damping) or in the initial inelastic range (premature damage).

When the tolerance in the SBC is exceeded, the force in the tension brace starts increasing, and the stiffness of the frame is recovered. The stiffness is somewhat lower than that of the DE system, where the compression brace is also active at this stage. However, the slip mechanism still acts at the compression brace which means that its contribution is not completely excluded, but only limited to the force S_0. Having in mind that this system is safe against bucking, this slight reduction of the stiffness is acceptable. It is obvious that at the end of this phase - when the elastic limit of the DEFD system is reached , the disposable elements of the conventional system are far beyond in the inelastic region. Indeed, the energy dissipation of the DE system is somewhat higher at this stage, but causing considerable damage of the DE during a moderate intensity earthquake. A frame equipped with a DEFD system would withstand such a earthquake without any damage, still possessing higher stiffness, strength and energy dissipation than a Moment Resisting Frame

While comparable with the conventional DE system at the lower response levels, the performance of the DEFD at the large storey drifts is superior. At the levels failures of the DEs of the conventional system are inevitable, the inelastic behaviour of this system is fully developed. Thus, the extremely large forces - which occur at this stage - can be distributed between the main frame and the auxiliary system. Obviously, the DEFD system can not completely exclude the main structure from damage during a severe earthquake, but it offers significant increase of the safety margin.

This system can be easily applied, using conventional construction techniques, without involvement of more advanced industries (necessary for manufacturing of components for active and base isolation systems, hydraulic dampers or even devices equipped with heavy-duty-brake-lining-pads) which would significantly raise the costs of the erection.

The experimental investigations have proved that regardless the observed shortcomings, the developed passive control system has a large capacity of energy absorption. Further investigations shall therefore be focused on elimination of the observed deficiencies in the recommended way for further research:

- Use of types of steel with higher strength characteristics and usage of a different technology in the fabrication of the plates and processing of slip surfaces.
- Incorporation of alloy shims (for example, brass shims), or shims of the same material that is used for the production of brake leaning pads in automobiles between the upper/lower and the middle plate.
- As an alternative to friction - Incorporation of rubber shims of different hardness instead of plates made of alloy.

CONCLUSIONS

Based on experimental and analytical investigations it can be concluded that the DEFD system offers a number of advantages:

- Initial strength and stiffness of any dual system, to constrain the unfavorable deflections under service load (wind, minor earthquakes).
- Controllable deformation of the structure, in linear and non-linear range.
- Presence of friction mechanism (SBC) enables dynamic characteristics of structure to vary with the amplitude of vibration, i.e. severity of excitation. Hence the phenomenon of resonance or quasi-resonance for future earthquakes is avoided.
- Considerable energy dissipation capacity at low excitation levels where other system do not offer any dissipation, apart from negligible viscous damping.
- The higher level of controllability means that by changing the tolerances and the slip force, the characteristics of the system can be varied. This can be very beneficial for application on various structures or in zones with different seismicity.
- The system does not require rigid connections between its elements (braces, slip plates, disposable rectangle). Thus, in case of damage, each of the parts can be easily replaced.
- The possibility of components fabrication, which this system offers, reduces the time required for construction of the structure

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