Mitigation assessment of passive seismic protection

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Abstract: - The intended contribution proposes a versatile approach of assessing the efficiency of seismic mitigation of passive seismic protection – via supplemental damping - of steel multi storey type structures. The efficiency of seismic mitigation is expressed in terms of reduction in the amplitudes of kinematical parameters (top lateral displacements, in this case) associated to seismically induced vibratory motion of the analyzed structures. The proposed approach may be applied to other parameters (story drifts, induced velocities and accelerations, ductility coefficients) describing static and kinematical states of steel skeletal structures seismically acted upon structures.

The proposed parameter for assessing efficiency of seismic protection is associated to the mitigation interval of steel frame type structures equipped with passive protection (viscous dampers). This interval is expressed in terms of both, time and fundamental natural period of vibrations of the structure and is considered from the moment when the vibratory motion is initiated till the moment the motion reaches its steady state. During this time interval, a clear picture of vibratory motion is exhibited: length of the interval, number of vibratory cycles, amplitudes, their variation / decrease in time, the end of transitory motion and the beginning of the (short, nevertheless) induced pseudo - steady state motion.

The intended contribution proposes a time variable parameter that synthesizes all these features of the transitory motion. The length of this interval is expressed in number of natural fundamental periods of vibrations and together with its descending slope emphasizes the effectiveness of seismic protection. The shorter is the interval and the greater is its descending slope, the more effective is the associated seismic protection.

Time history type analyses have been carried out on several sets of skeletal steel structures. The structures are analyzed in two cases: without seismic protection (reference structure) and equipped with passive seismic protection (viscous dampers). The numerical results of time history analyses are presented and discussed with reference to the proposed parameter assessing seismic mitigation. The time variation of the proposed parameter is presented graphically for a better and immediate “physical” perception. The effectiveness of the seismic passive protection is discussed in terms of proposed parameter.

Key-Words: - steel skeletal structures, viscous dampers, time history analysis, seismic mitigation curves

1 Introduction
The reduction of seismic response to an input earthquake associated to location area is the immediate and popular meaning of seismic protection of structures. Reduction of seismic response has to be expressed in several static and kinematical parameters. Though, in seismic structural design, it is both, customary and code provided, to subject a structure to a statically equivalent loading, the efficiency of seismic protection is more relevant when it is expressed in terms of reduction in the peak values of induced kinematical parameters. When these parameters are lateral top displacements (as it is the case of a multi-storey structure), the seismic protection is, almost, physically perceptible. A dramatic reduction in values of top lateral displacements of a skeletal structure induced by a strong earthquake is, no less than a symbol of a seismic protection system. Earthquake induced kinematical parameters associated to top structural levels are both, very popular in being connected to seismic protection and, also, very versatile in presenting the level of seismic protectiveness in a comparative manner [1], [2], [3]. Nevertheless, it is important to point out that a passive seismic protection via viscous dampers will result in visible change (decrease) in lateral displacements while, the changes (reductions) in accelerations are not significant.

If seismically induced kinematical parameters (displacements, velocities, accelerations) are to be analyzed, seismic behaviour of frame type steel structures exhibits three distinct intervals:

1. A first interval, exhibiting ascending values of seismically induced kinematical parameters, mainly lateral displacements. The values increase rapidly in their both, positive and negative amounts. Time variation and absolute values depend on input accelerogram and inertial properties of the structure.
2. The second interval is associated to the large (including peak values) of input accelerogram. Large oscillatory values of static and kinematical states are developed. The large values of displacements and stresses are responsible for damages in skeletal structures: cracks, formation of plastic zones, yielding in tensioned steel, buckling of compressed members. A damaging shakedown type structural behaviour may be reached.

3. The third, ending interval is associated to a reduction in acceleration values down to their complete diminishing. The structural response is unpredictable as several structural members may be damaged.

Where should a seismic efficient protection operate to induce a rapid seismic mitigation? The second interval seem to be the most appropriate for this by reducing both, its lengths and values of corresponding parameters (displacements). A seismic protection system, fully and efficiently operating in this interval, will avoid the shakedown type behaviour and initiate a progressive descending behaviour. The more rapidly is the mitigation interval initiated and the steeper is its form, the more seismically efficient is the protection system. The present contribution focuses on the versatility of the envelop curves that collect the peak values of kinematical parameters to express the efficiency of seismic protection. The envelop curves are referred to as “seismic protection efficiency curves” (SPEC).

The study deals with computing, assessing and comparing the efficiency of seismic protection via viscous dampers from the point of view of this mitigation interval via seismic protection efficiency curves. The study has been conducted on a large set of steel frames designed for office buildings located in a highly seismically area of Romania. From a larger set of studied structures, a twelve story five bay frame has been selected and the presented and commented numerical results are associated to this structure. The frame is acted upon by Vrancea (Romania 1977) recorded earthquake accelerogram (a reference accelerogram) and, also, by a sinusoidal accelerogram. The sinusoidal accelerogram avoids mitigation effect associated to the decrease in the values of a natural accelerogram. Both accelerograms are applied on the structure acted upon by dead and live loadings (design code combination) associated to office building serviceability.

A reference seismically unprotected frame and three alternatives (of added viscous damping levels) of seismic protection are analysed. The seismic protection consists of twelve viscous dampers, placed in the central bay along the entire height of the structure. The three alternatives of seismic protection are approximately equivalent to a general inherent damping level of 10%, 15% and 20% respectively.

Performed analyses are of time-history type. Computed parameters are lateral top displacements with a special focus on the form (length and steepness) of the mitigation interval. The graphical representation of the mitigation effect – through seismic protection efficiency curves (SPEC) - of seismic protection has been considered more perceptible and eloquent. A special issue related to the mitigation interval is the amount of reduction in (usually) peak values of computed kinematical parameter. Nevertheless, a question has to be answered: in what conditions may an oscillatory seismically induced motion (irrefutably transitory) be considered a steady state motion? This question is responsible for introducing – in the present study - a sinusoidal type accelerogram. By exhibiting an indefinite steady state characteristic, a sinusoidal accelerogram can be associated to a real steady state motion induced into the analyzed structure. Under a sinusoidal type action, the mitigation interval and the steady state motion can be clearly defined. A recorded seismic accelerogram will, always, display a pseudo steady state motion.

2 Analyzed structures
The two classes of frames (reference frame – Fig. 1) and equipped with viscous dampers frames (Fig. 2) have the same general and sectional geometry. The cross section dimensioning has been performed according to current Romanian design provisions for steel structures. Loading combination includes both, gravitational loads and seismic action A general level of stressing of approximately 75% of full (bending) capacity of the frame members is reached. The sections of elements, also, observe design provisions with reference to local stability and deformation state.

Fig.1 Reference frame
Fig. 2 Frame with viscous dampers

A previous study, regarding the influence of dampers location in the frame on protection efficiency, lead to the present placement: in the central bay along the entire height of the structure (Fig. 2).

The intensity of sinusoidal accelerogram (Fig. 4) has been fixed at 0.2g, corresponding to the maximum value of recorded Vrancea N-S (March 1977, Romania) accelerogram (Fig. 3). Vrancea 1977 earthquake exhibited a 7.2 magnitude on Richter scale (maximum predicted magnitude is 7.5) and lasted 50 seconds approximately. By its destructions and casualties, Vrancea 1977 earthquake is considered a reference earthquake in this country.

Regarding the aspect of the global level of damping induced into the structure via viscous dampers, it has been dealt with by using seismic response displacement code spectra for several levels of damping [4]. Induced level of damping has been equated to the damping level of code displacement spectra when producing the same displacements. In this way, a natural (inherent) level of 5% and three artificially induced damping levels (via viscous dampers) of approximately 10%, 15% and 20% respectively have been taken into account in the performed analyses.

The dampers are of FIP INDUSTRIALE type [5] and are of nonlinear viscous type. The damping force of each damper is given by \( F_v = c \times v^{0.15} \) [5], where \( c \) is an adaptable damping coefficient (its values have been computed for each global damping level) and \( v \) is velocity of motion and it is implicitly computed.

3 Numerical Results

Several sets of numerical results have been obtained. The focus of this contribution is especially on the mitigation interval of lateral top displacements. Seismic protection efficiency is expressed, both graphically and numerically by computed (envelop) seismic protection efficiency curves (SPEC’s) that collect the peak values of induced top lateral displacements. In the case of recorded Vrancea 1977 accelerogram, and in the case of sinusoidal type accelerogram, the displacements versus time presented diagrams have been extracted from the entire diagram (associated to the real duration of earthquake, approximately 50 seconds), such that “extracted segments” comprise the mitigation intervals in order to allow for a better assessment of the length and slope of SPEC’s. The computed numerical results are presented in a comparative manner; the cases of supplemental damping are presented versus the homologous results related to the reference structure.

The seismic protection efficiency curves (SPEC’s) have been computed as envelope curves of peak (positive and negative) values of displacement versus time diagrams. In this way, the steepness of these envelope curves expresses both, the length (in time) of the mitigation interval and the amount of reduction in the peak values of the kinematical parameters (displacements, in this case).

When the reduction in the displacements values reaches approximately 70% of their maximum values, the steady state motion is considered initiated. Presented numerical results refer to displacements variation with time of top lateral displacement in the case of Vrancea earthquake (Fig. 3) for the reference frame and three levels of supplemental damping: 10% (Fig. 5), reference frame and 15% supplemental damping (Fig. 6) and reference frame and 20% supplemental damping (Fig. 7).
Fig. 5 Displacements - reference frame versus frame with 10% damping (VRANCEA)

Fig. 8 Displacements - reference frame versus frame with 10% damping (Sinusoidal)

Fig. 6 Displacements - reference frame versus frame with 15% damping (VRANCEA)

Fig. 9 Displacements - reference frame versus frame with 15% damping (Sinusoidal)

Fig. 7 Displacements - reference frame versus frame with 20% damping (VRANCEA)

Fig. 10 Displacements - reference frame versus frame with 20% damping (Sinusoidal)
Fig. 11 Displacement mitigation curves - reference frame versus frame with 10% damping (VRANCEA)

Fig. 12 Displacement mitigation curves - reference frame versus frame with 15% damping (VRANCEA)

Fig. 13 Displacement mitigation curves - reference frame versus frame with 20% damping (VRANCEA)

Fig. 14 Displacement mitigation curves - reference frame versus frame with 10% damping (sinusoidal)

Fig. 15 Displacement mitigation curves - reference frame versus frame with 15% damping (sinusoidal)

Fig. 16 Displacement mitigation curves - reference frame versus frame with 20% damping (sinusoidal)
Similar results are presented in the case of sinusoidal accelerogram: reference frame versus 10% supplemental damping (Fig. 8) reference frame versus 15% supplemental damping (Fig. 9) and reference frame versus 20% supplemental damping (Fig. 10), respectively.

Corresponding seismic mitigation curves (SPEC’s) for above study cases are presented in Fig. 11, Fig 12 and Fig. 13 – for Vrancea 1977 earthquake and in Fig. 14, Fig. 15 and Fig. 16, respectively – for sinusoidal type excitation.

The efficiency of supplemental damping in saving the structure of shakedown type behaviour may be emphasized by expressing the mitigation interval in terms of fundamental natural period $T_1$ of analyzed structure. Scaling the seismic mitigation interval in terms of (fundamental) natural period of the structure, rather than in time units, allows for expressing the efficiency of seismic protection (level of supplemental damping) in number of cycles of seismically induced vibrations. The proposed seismic protection efficiency curves (SPEC’s) underline – by their slope and length - the duration and rapidity of the seismic mitigation in terms of the natural fundamental periods of vibration of analysed structure.

### 4 Conclusions

The final inferred conclusions refer to the efficiency of the seismic protection via viscous dampers and, mainly, to the possibility of assessing this efficiency via proposed seismic mitigation envelope curve (SPEC). An inherent [6] damping level of 5% is considered as a standard unit of damping level. Therefore, a damping level of 10% is equivalent with a two unit level, a damping level of 15%, is referred to, as a 3 unit level, while a 20% (highest in this study) damping level will be a 4 unit damping level.

Using such a scaled damping level, it may be concluded that a doubling in the damping level (from standard 5% to 2 unit level of 10%) results in a reduction in top lateral displacements of 10 %, while a threefold increase induces a decrease of 14 % in lateral top displacements. The (20%) level of damping is equivalent to a reduction of 16% (in the case of Vrancea accelerogram). Similar reductions in lateral top displacements (of 21%, 30% and 50%), respectively are associated to the case of sinusoidal excitation. The proposed mitigation envelope curves (SPEC’s) are eloquent in terms of the length of the interval expressed in the natural fundamental period. In the case of reference frame, the length of the mitigation interval is reduced from 7$T_1$ to 3$T_1$ in the case of 10% added damping and Vrancea accelerogram, (Fig. 11). Similarly, SPEC’s associated to 15% and 20% levels of added damping are, also, computed (Fig. 12, Fig. 13).

Associated results for the sinusoidal type excitations are presented in the same manner: in the case of 10% supplemental damping (Fig. 14), in the case of 15% added damping (Fig. 15) and in the case of 20%, respectively (Fig. 16).

The proposed mitigation enveloped curves (SPEC’s) prove to be a versatile tool of assessing the efficiency of supplemental damping. Their expressing in terms of fundamental natural period of the structure allows a rapid and synthetic evaluation of supplemental damping efficiency. A vibration “stage” along a time interval up to two fundamental periods ($2T_1$) may save the structure of a shakedown behavior and, consequently, of damaging remanent deformations. It may be concluded that the decrease in the values of top lateral displacements expressed in terms of fundamental vibration period offers immediate asses of the measure of reductions in these values. The versatility of mitigation envelope curves and their synthetic feature opens the possibility of including them in the set of performance criteria of seismically protected steel structures.

### References:


