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.

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 (approximate) 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 refer to the variation of top lateral displacements ant the top lateral (induced) accelerations. The results 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. Though not so much attractive as the variation of lateral displacements, the variation of induced lateral accelerations is, also, a source of information about the efficiency of seismic protection or rather, about the efficiency of supplemental damping [1]. 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 [2]. 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 [3].

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 or when 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, accelerations). 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 (displacements and accelerations) 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 mitigation interval has a vital importance by both, its amount of diminishing the induced seismic effects as well as its location versus seismic action duration.

The study has been conducted on a large set of steel skeletal structures designed for office buildings located in a highly seismic area of Romania. The set of frames that have been studied comprises four structures of planar frames type of six, nine, twelve and fifteen stories respectively. The structures are acted upon by Vrancea 1977 (Romania) recorded accelerogram (a reference accelerogram for Romania) and, also, by a sinusoidal accelerogram, both applied in the presence of gravitational loading (associated to an office building serviceability). The sinusoidal type accelerogram has been applied in order to distinguish mitigation effects due to the inherent transitory nature of seismic effect from mitigation effects due to supplemental damping.

A reference frame (seismically unprotected of 5% general inherent damping level) is considered and three supplemental viscous damping levels (of approximately 10%, 15% and 20%, respectively) are taken into account. The supplemental damping is provided by viscous dampers located in the middle span along the entire height of the structures.

Performed analyses are of time history type. Computed parameters are top lateral displacements and accelerations with a special focus on the forms (length and steepness) of mitigation interval. The length of mitigation interval is expressed in number of natural (fundamental) periods of the structure. The end of the mitigation interval is associated to the starting of a pseudo – steady state of vibratory motion. In its turn, steady state motion is considered when the reduction in peak values of lateral top displacements reaches 70%. In the case of earthquake accelerogram, the vibratory motion following the mitigation interval is a pseudo-steady state motion due to the irrefutable transitory feature of seismic action, while in the case of sinusoidal type accelerogram, the mitigated motion has, indeed, a steady state aspect.

Obtained results are presented *in extenso* for the 15 and 12 stories frames, while the results associated to 6 stories, 9 stories frames are only presented in a comparative manner.

2 Analyzed structures

The two sets of frames (a set of seismically unprotected frames and a set of seismically protected frames) have the same general and sectional geometry. The 12 stories reference frame (Fig. 1) and the 15 stories frames reference frame (Fig. 2) have been designed according to current Romanian design provisions for steel structures. [4] and observe, also, European recommendations [5] for steel skeletal 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.

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 [6]. Induced level of damping has been equated to the damping level of code displacement spectra that yields (produces) the same displacements. Substituting displacements by accelerations into above equating process, the obtained results are close.

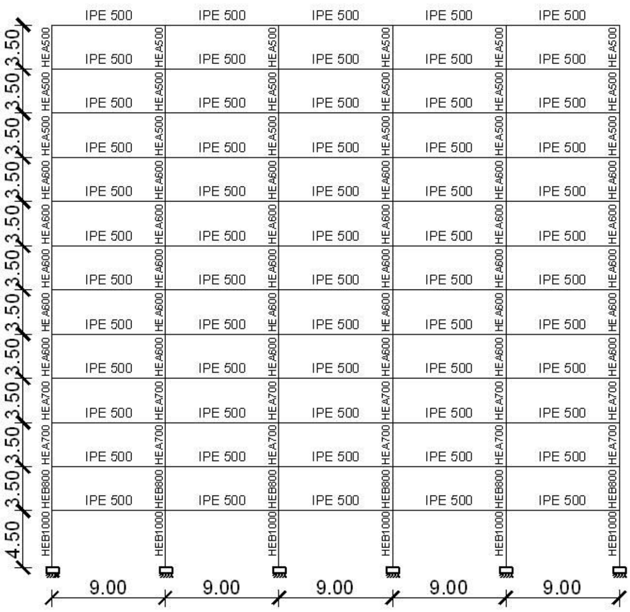

Fig.1 Twelve stories reference frame

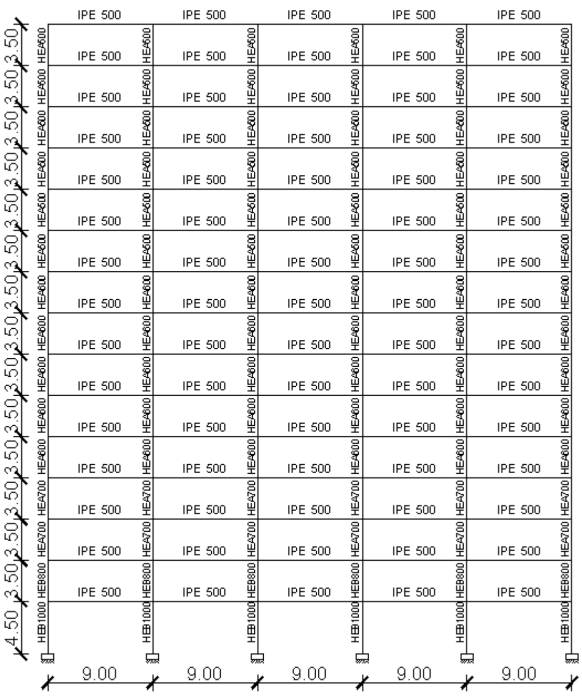

Fig.2 Fifteen stories reference frame

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. 3) for all frames.
The intensity of sinusoidal accelerogram (Fig. 5) has been fixed at 0.2g, corresponding to the maximum value of recorded Vrancea N-S (March 1977, Romania) accelerogram (Fig. 4). 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.

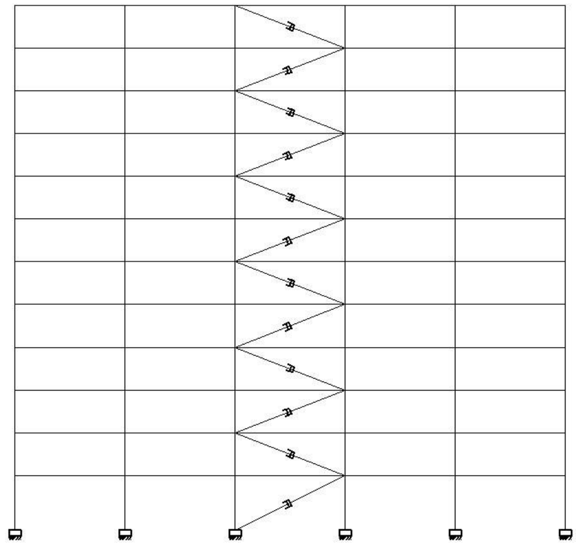
Fig.3 Frame with viscous dampers

The sinusoidal accelerogram (Fig. 5) acts, rather as a dynamic action of indefinite duration in time. By this artificial action, no reduction in seismically induced effects is recorded due the diminishing of the (seismic) action itself as it happens in the case of a recorded accelerogram. The sinusoidal accelerogram may be compared to a dynamic force of constant amplitude, therefore the mitigation effects of added damping will exhibit only the amount of mitigation (reduction) not the duration and location of the mitigation interval allowing for a better assessment of added damping.

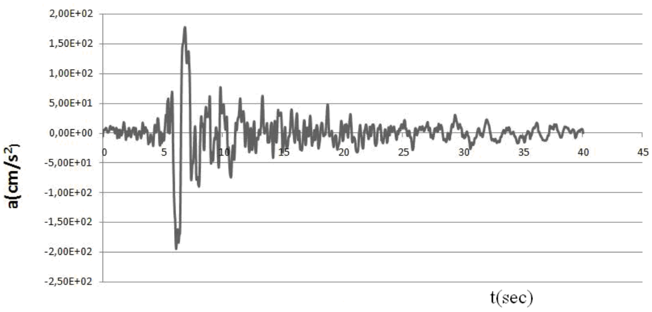

Fig. 4 Vrancea 1977 accelerogram

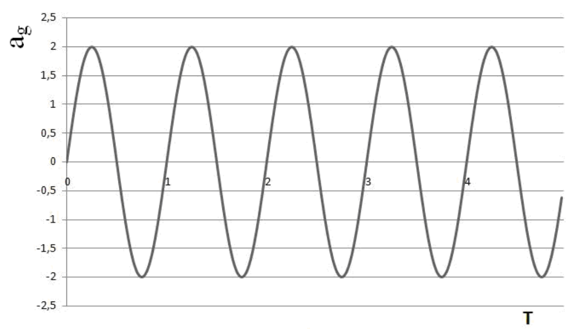

Fig. 5 Sinusoidal accelerogram

The dampers are of FIP INDUSTRIALE type and are of nonlinear viscous type. The damping force of each damper is given by $F_a=c*v^{0.15}$ [7], 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. The nonlinearity is generated by the exponential factor $v^{0.15}$.

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 and lateral top accelerations. 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 and accelerations, in this case). When the reduction in the displacements values reaches approximately 70% of their maximum values, the steady state motion is considered initiated.

3.1 Variation of displacements

The results referring to the variation of top lateral displacement in the case of 12 stories frame acted upon by Vrancea earthquake (Fig. 4) for the reference frame and three levels of supplemental damping are presented together as follows: reference frame and 10% supplemental general level of damping (Fig. 6), reference frame and 15% supplemental damping (Fig. 7) and reference frame and 20% supplemental damping (Fig. 8). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements: reference frame and 10% supplemental general level of damping (Fig. 9), reference frame and 15% supplemental damping (Fig. 10) and reference frame and 20% supplemental damping (Fig. 11).

Expressing the efficiency of seismic protection in number of cycles of seismically induced vibrations proves to be more perceptible.

The proposed SPEC's are presented in the same comparative manner as the displacements: reference frame and 10% supplemental general level of damping (Fig. 12), reference frame and 15% supplemental damping (Fig. 13) and reference frame and 20% supplemental damping (Fig. 14). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements via SPEC's as follows: reference frame and 10% supplemental general level of damping (Fig. 15), reference frame and 15% supplemental damping (Fig. 16) and reference frame and 20% supplemental damping (Fig. 17).

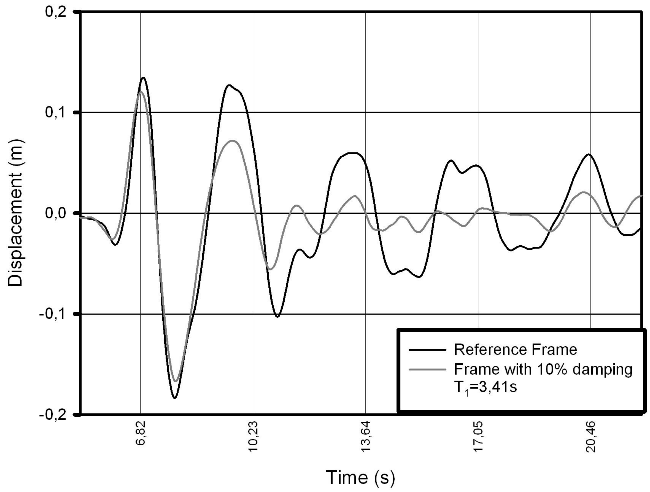

Fig. 6 Displacements - reference frame versus frame with 10% damping (VRANCEA)

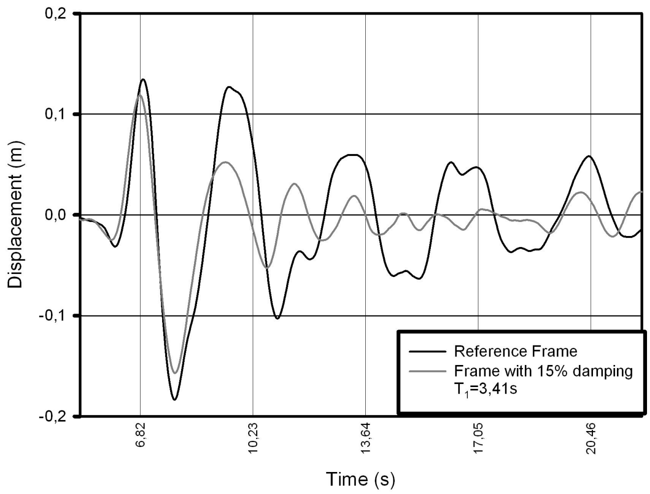

Fig. 7 Displacements - reference frame versus frame with 15% damping (VRANCEA)

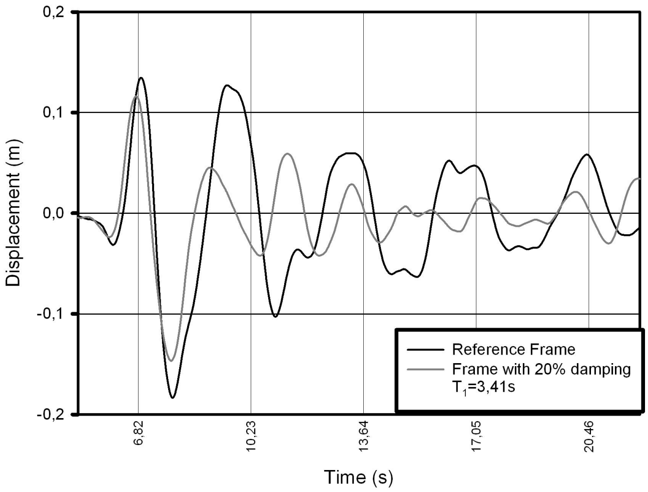

Fig. 8 Displacements - reference frame versus frame with 20% damping (VRANCEA)

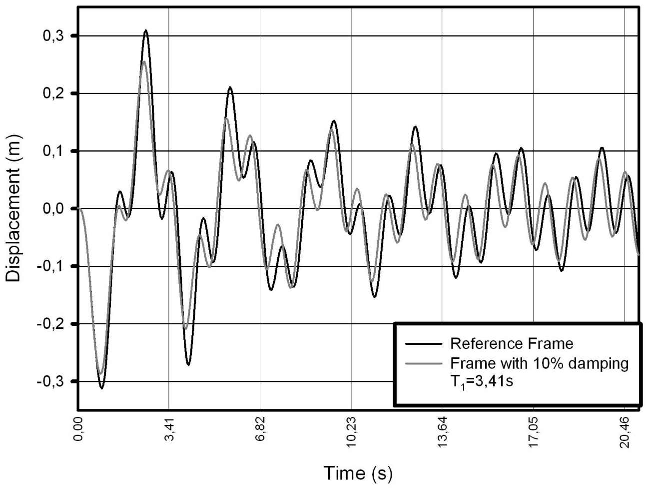

Fig. 9 Displacements - reference frame versus frame with 10% damping (Sinusoidal)

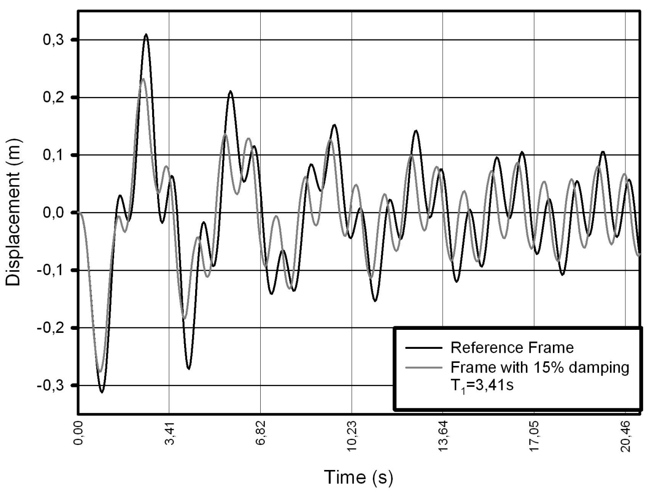

Fig. 10 Displacements - reference frame versus frame with 15% damping (Sinusoidal)

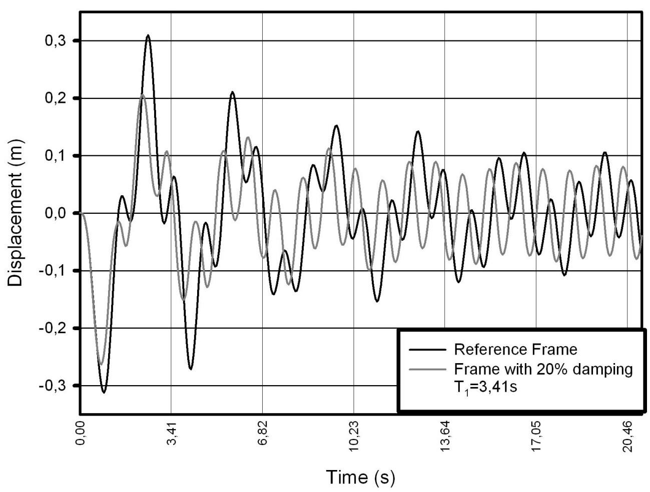

Fig. 11 Displacements - reference frame versus frame with 20% damping (Sinusoidal)

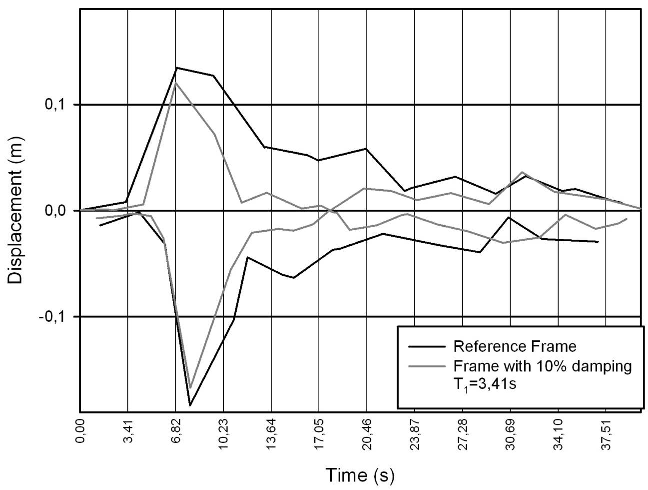

Fig. 12 Displacement mitigation curves - reference frame versus frame with 10% damping (VRANCEA)

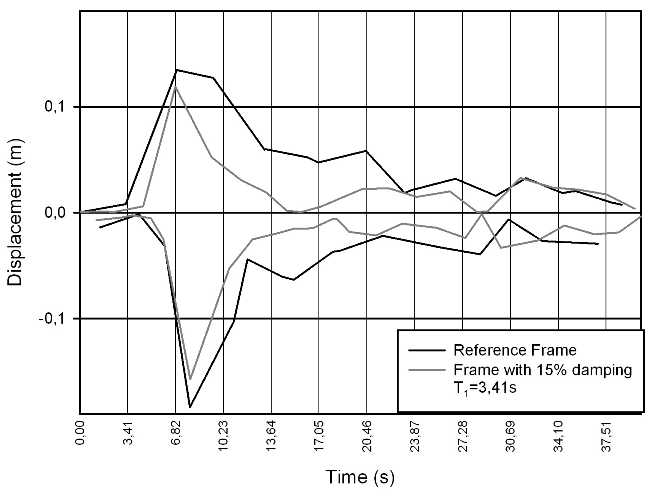

Fig. 13 Displacement mitigation curves - reference frame versus frame with 15% damping (VRANCEA)

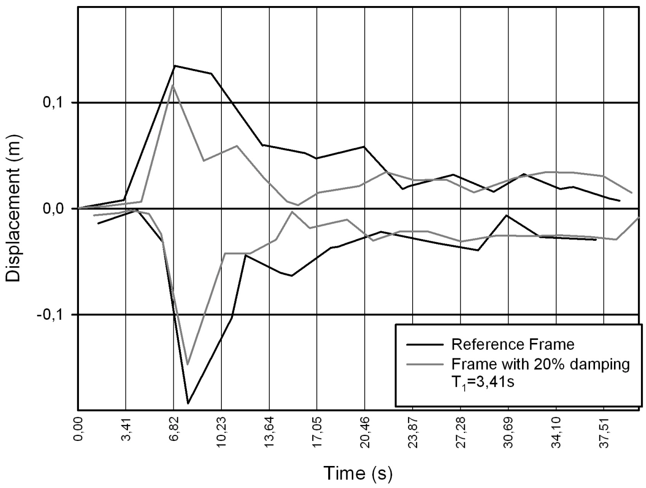

Fig. 14 Displacement mitigation curves - reference frame versus frame with 20% damping (VRANCEA)

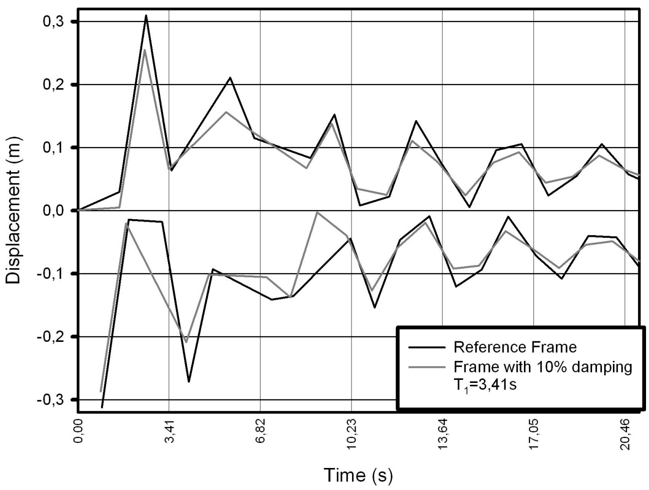

Fig. 15 Displacement mitigation curves - reference frame versus frame with 10% damping (sinusoidal)

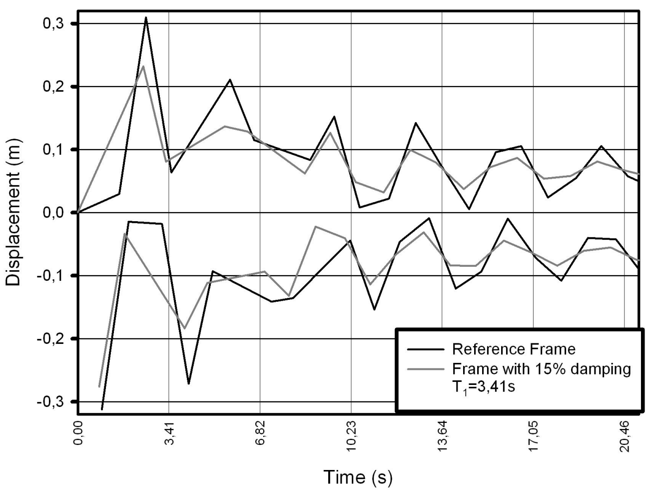

Fig. 16 Displacement mitigation curves - reference frame versus frame with 15% damping (sinusoidal)

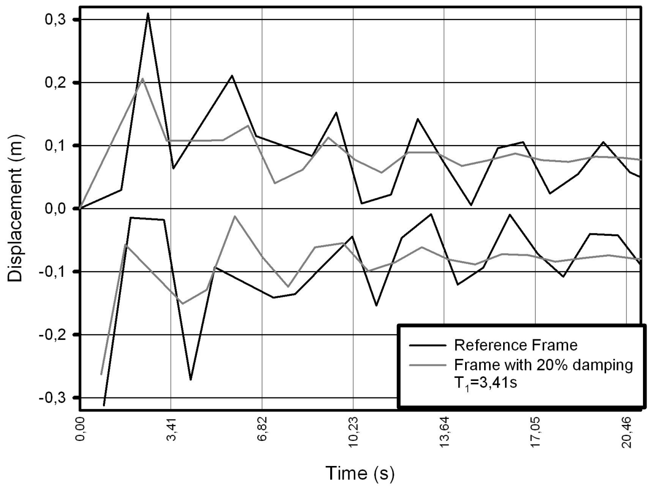

Fig. 17 Displacement mitigation curves - reference frame versus frame with 20% damping (sinusoidal)

Similar results have been obtained in the case of 15 stories frame. Presentation of the results associated to 15 stories frame follows the same pattern as in the case of 12 stories frame: reference frame and 10% supplemental general level of damping (Fig. 18), reference frame and 15% supplemental damping (Fig. 19) and reference frame and 20% supplemental damping (Fig. 20). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements: reference frame and 10% supplemental general level of damping (Fig. 21), reference frame and 15% supplemental damping (Fig. 22) and reference frame and 20% supplemental damping (Fig. 23).

As it has been underlined, SPEC's are scaled in terms of (fundamental) natural period of vibration, rather than in time. The proposed SPEC's are presented in the same comparative manner as the displacements: reference frame and 10% supplemental general level of damping (Fig. 24), reference frame and 15% supplemental damping (Fig. 25) and reference frame and 20% supplemental damping (Fig. 26). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements via SPEC's as follows: reference frame and 10% supplemental general level of damping (Fig. 27), reference frame and 15% supplemental damping (Fig. 28) and reference frame and 20% supplemental damping (Fig. 29).

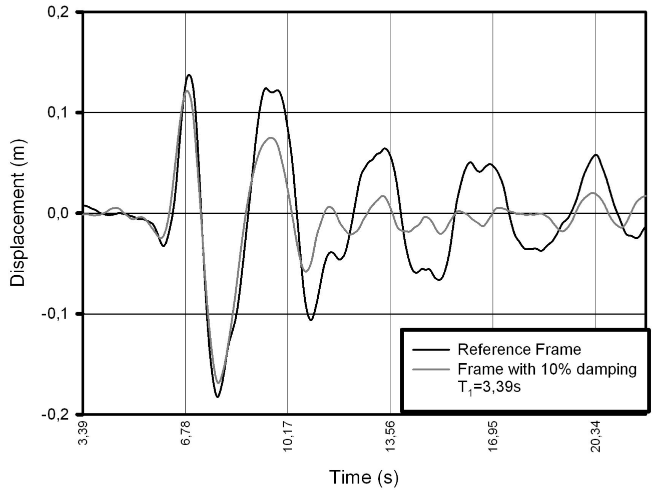

Fig. 18 Displacements - reference frame versus frame with 10% damping (VRANCEA)

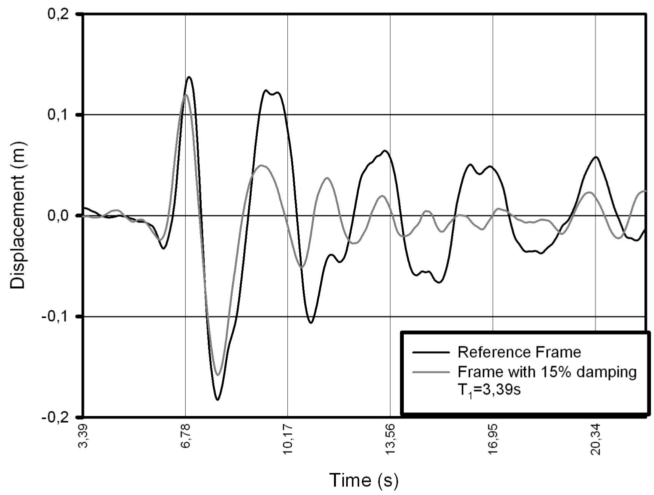

Fig. 19 Displacements - reference frame versus frame with 15% damping (VRANCEA)

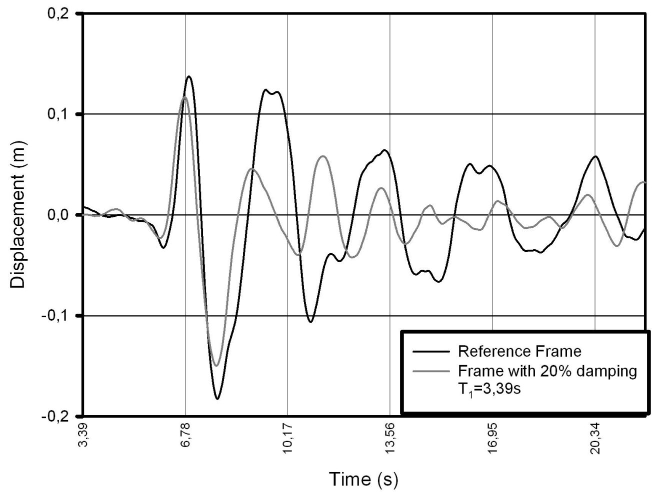

Fig. 20 Displacements - reference frame versus frame with 20% damping (VRANCEA)

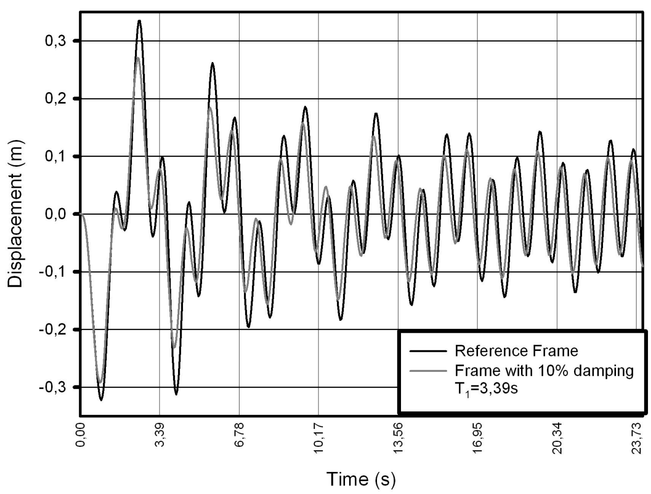

Fig. 21 Displacements - reference frame versus frame with 10% damping (Sinusoidal)

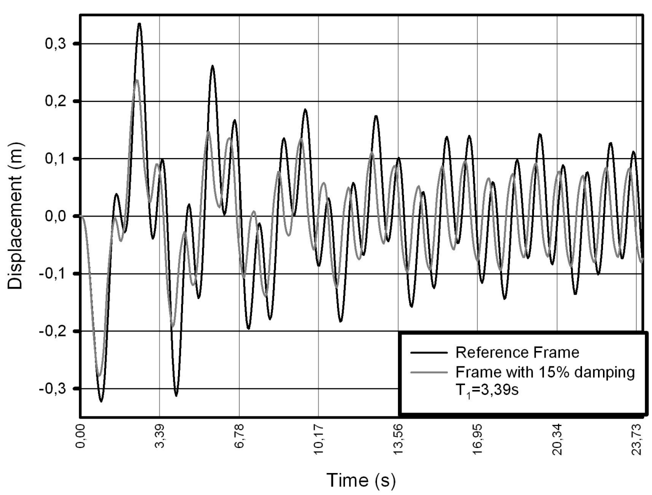

Fig. 22 Displacements - reference frame versus frame with 15% damping (Sinusoidal)

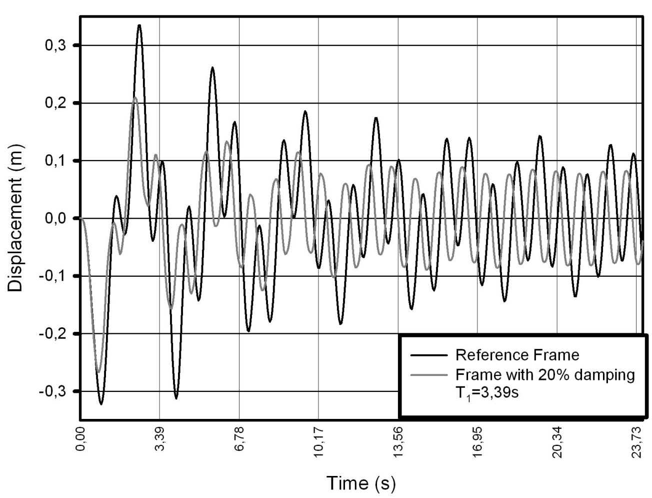

Fig. 23 Displacements - reference frame versus frame with 20% damping (Sinusoidal)

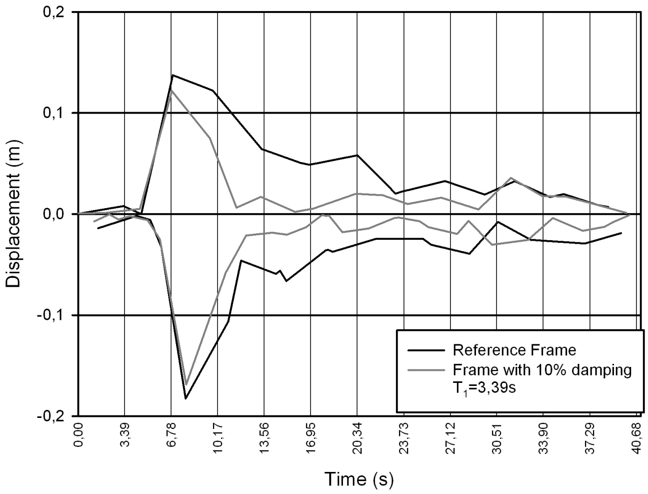

Fig. 24 Displacement mitigation curves - reference frame versus frame with 10% damping (VRANCEA)

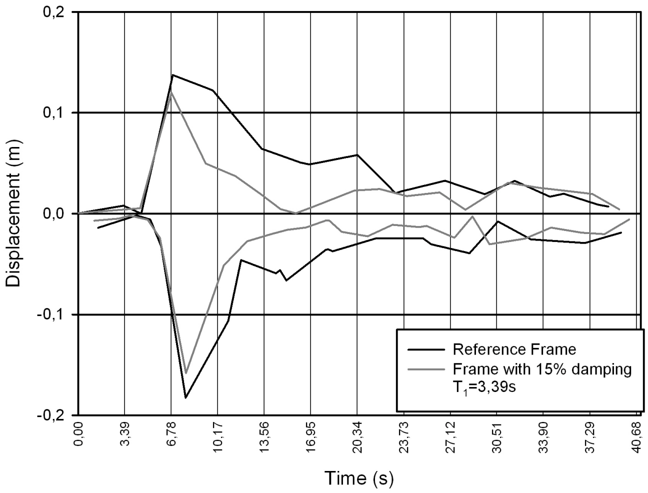

Fig. 25 Displacement mitigation curves - reference frame versus frame with 15% damping (VRANCEA)

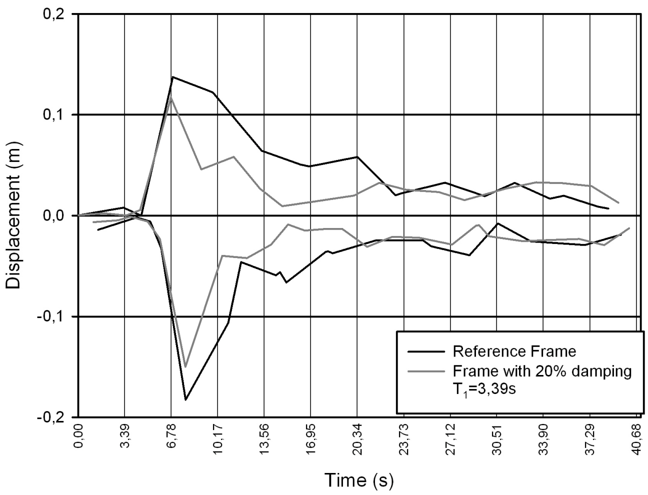

Fig. 26 Displacement mitigation curves - reference frame versus frame with 20% damping (VRANCEA)

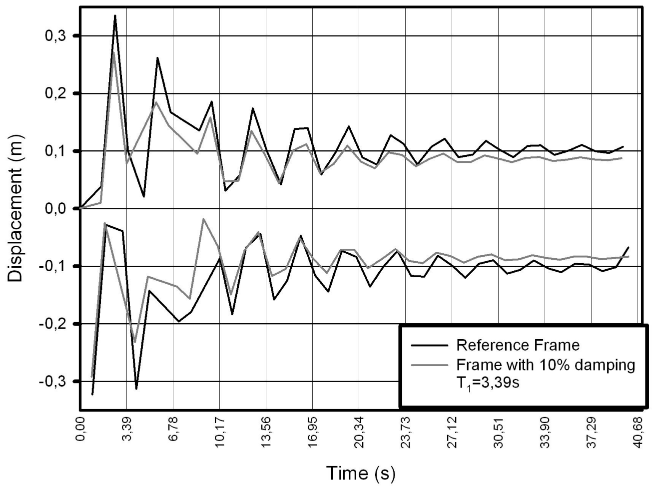

Fig. 27 Displacement mitigation curves - reference frame versus frame with 10% damping (sinusoidal)

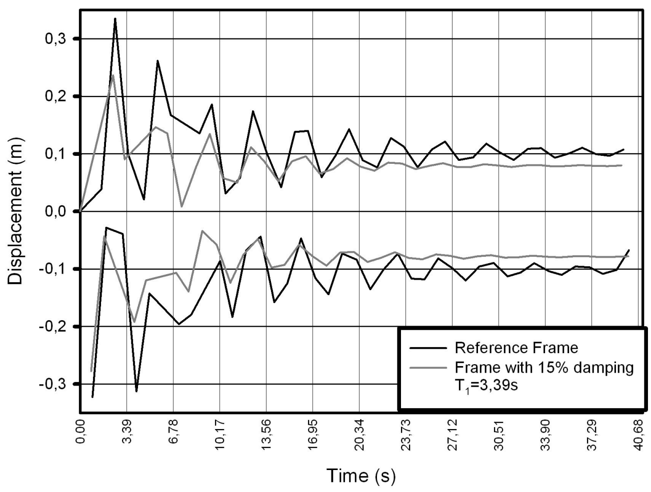

Fig. 28 Displacement mitigation curves - reference frame versus frame with 15% damping (sinusoidal)

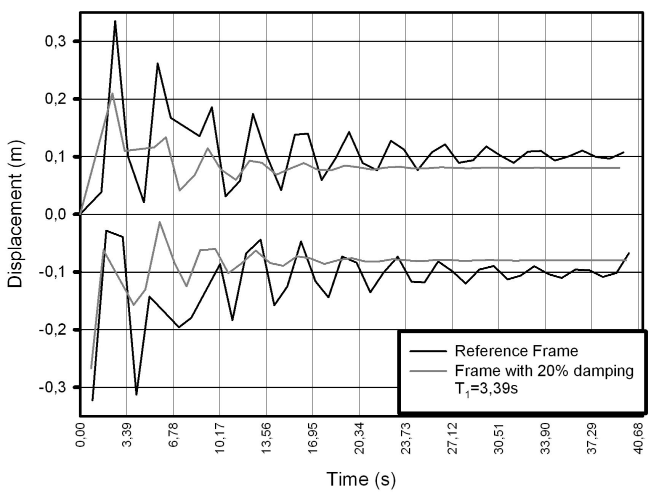

Fig. 29 Displacement mitigation curves - reference frame versus frame with 20% damping (sinusoidal)

3.2 Variation of accelerations

At this stage, a short statement of “why (induced) accelerations” and “not only (induced) displacements” have been considered for assessing the seismic protection efficiency is necessary. Indeed, what else than lateral displacements of top level may better express induced seismic effects? The displacements (mainly lateral top displacements, in the case of skeletal multi-storey structures) are both, very discernible and very popular as they, actually, perform the seismically induced lateral sway motion of these structures. Present contribution is part of a larger study that includes several seismically induced, both kinematical (displacements, velocities, accelerations, story drifts, ductility coefficients) and static (base shear, statically equivalent seismic forces) parameters.

Computed induced accelerations have been selected in the present work, as the reductions in their (peak) values are not spectacular. The (small) reductions in induced accelerations are rather disappointing when compared to the reductions in displacements and, also, when compared to the amount of added damping (up to 4 times the inherent damping amount). Nevertheless, the accelerations are very eloquent when they are regarded in relation with statically equivalent seismic forces. A straightforward and direct proportionality relate accelerations to statically equivalent seismic forces. Therefore, even if displacements are dramatically reduced, only the accelerations “tell he truth” about reduction in seismic effects. As long as the structural seismic design process follows the “statically equivalent seismic forces” pattern, the seismic mitigation has to be asses in terms of accelerations rather than in terms of displacements. Reduction in (peak values of) induced accelerations is the real reward to the supplemental damping introduced into the structure via viscous dampers.

The small reduction in induced accelerations (as compared to the larger reduction in induced displacements) is, also, a direct consequence of the apparently insignificant change in natural period / circular frequency of vibrating mechanical systems in the presence of viscous damping versus the values of homologous parameters computed in the case of undamped vibrations [8], [9], [10]. Nevertheless, a small amount of reduction in induced accelerations has to be always related to the large values of vibrating masses of multi - storey structures.

The results referring to the variation of top lateral acceleration in the case of 12 stories frame acted upon by Vrancea earthquake (Fig. 4) for the reference frame and three levels of supplemental damping are presented together as follows: reference frame and 10% supplemental general level of damping (Fig. 30), reference frame and 15% supplemental damping (Fig. 31) and reference frame and 20% supplemental damping (Fig. 32). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral accelerations: reference frame and 10% supplemental general level of damping (Fig. 33), reference frame and 15% supplemental damping (Fig. 34) and reference frame and 20% supplemental damping (Fig. 35).

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. In this way, 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.

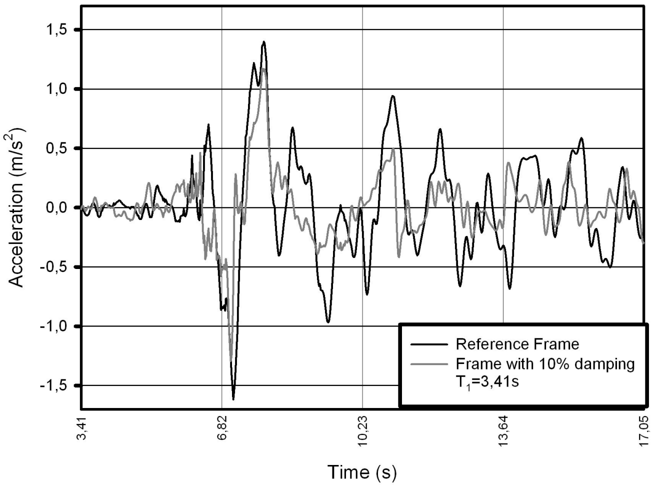

Fig. 30 Acceleration - reference frame versus frame with 10% damping (VRANCEA)

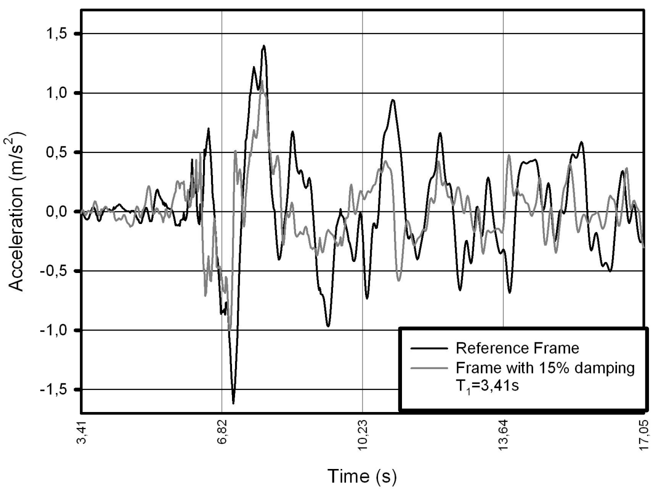

Fig. 31 Acceleration - reference frame versus frame with 15% damping (VRANCEA)

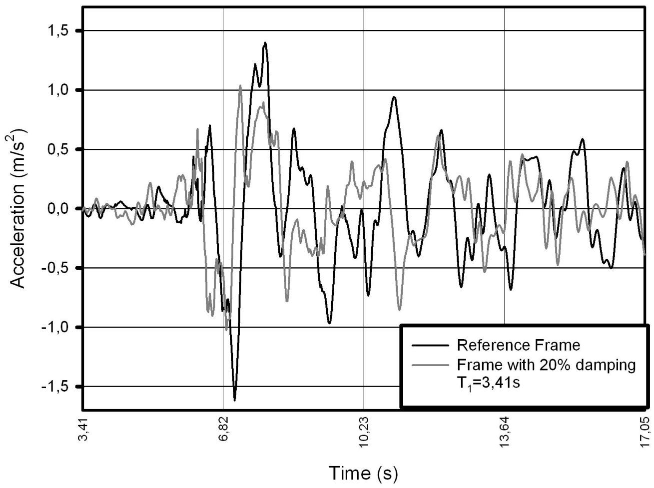

Fig. 32 Acceleration - reference frame versus frame with 20% damping (VRANCEA)

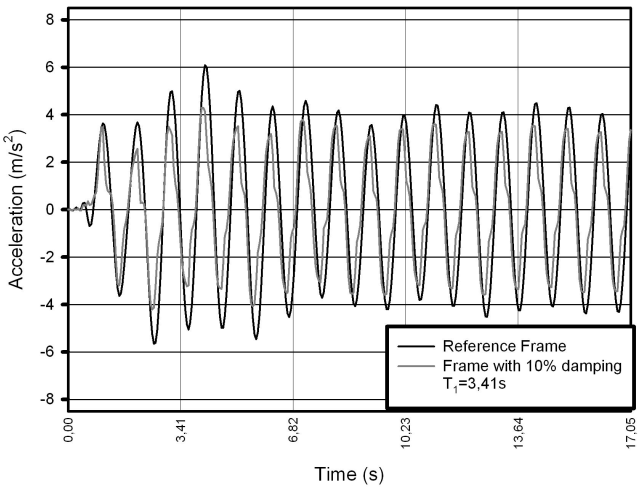

Fig. 33 Acceleration - reference frame versus frame with 10% damping (Sinusoidal)

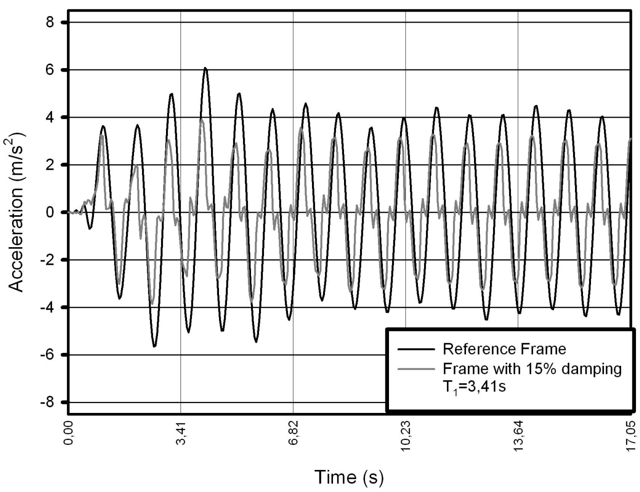

Fig. 34 Acceleration - reference frame versus frame with 15% damping (Sinusoidal)

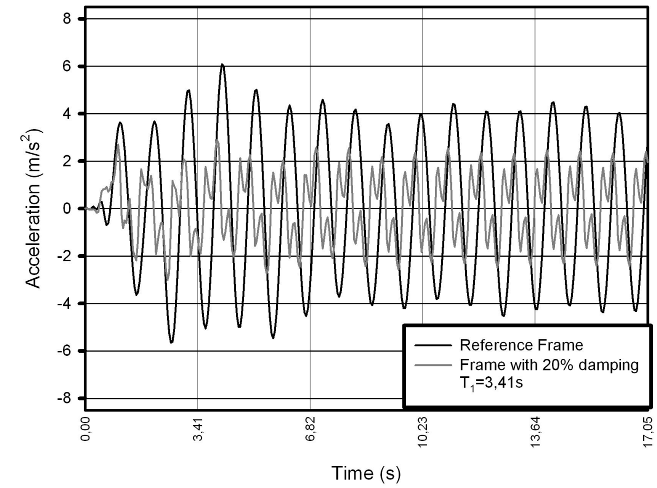

Fig. 35 Acceleration - reference frame versus frame with 20% damping (Sinusoidal)

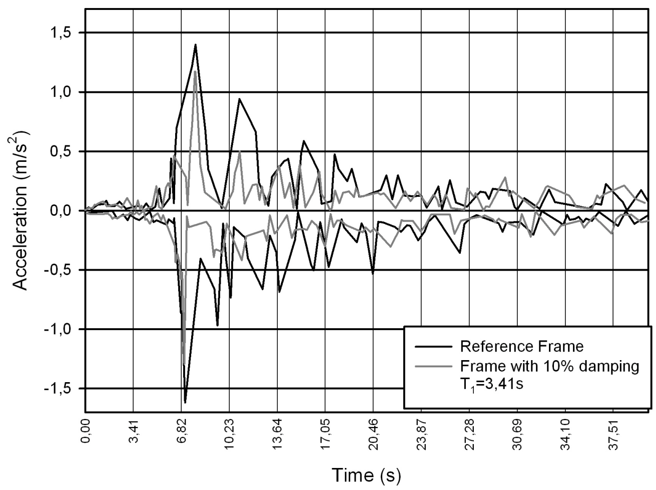

Fig. 36 Acceleration mitigation curves - reference frame versus frame with 10% damping (VRANCEA)

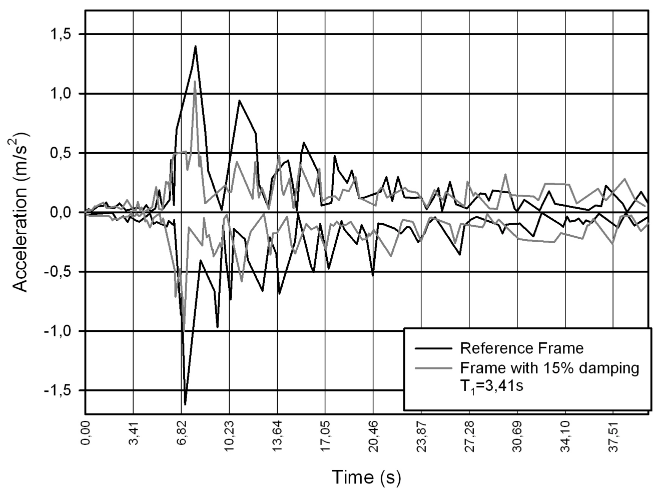

Fig. 37 Acceleration mitigation curves - reference frame versus frame with 15% damping (VRANCEA)

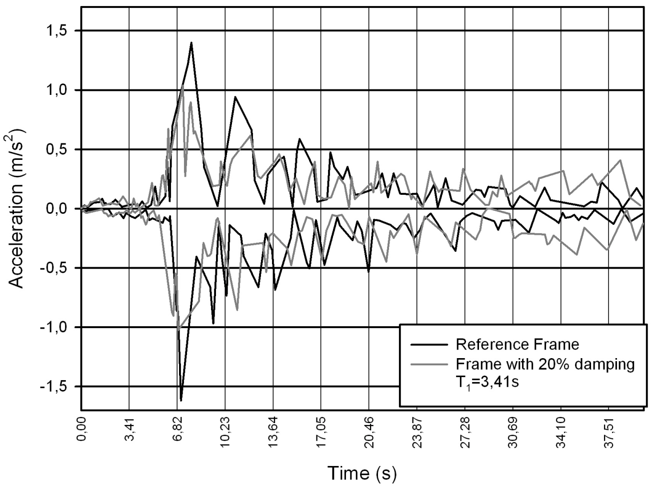

Fig. 38 Acceleration mitigation curves - reference frame versus frame with 20% damping (VRANCEA)

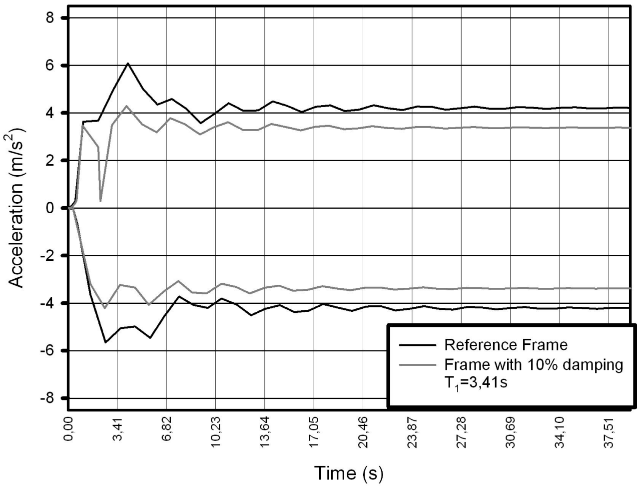

Fig. 39 Acceleration mitigation curves - reference frame versus frame with 10% damping (sinusoidal)

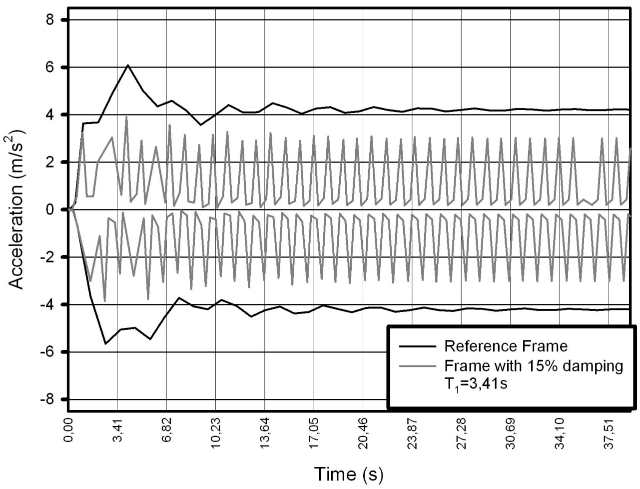

Fig. 40 Acceleration mitigation curves - reference frame versus frame with 15% damping (sinusoidal)

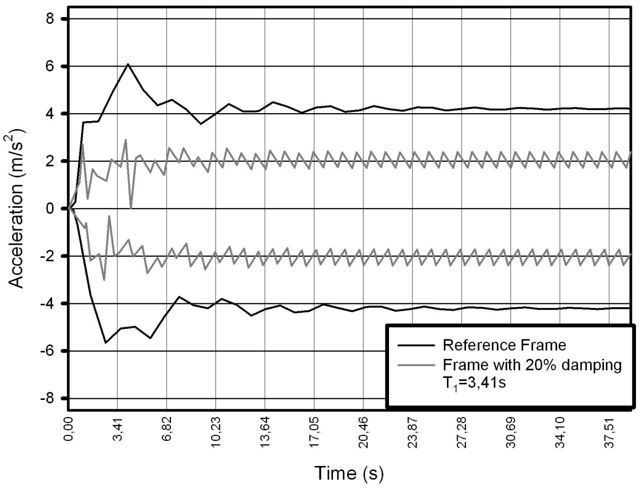

Fig. 41 Acceleration mitigation curves - reference frame versus frame with 20% damping (sinusoidal)

The proposed SPEC's are presented in the same comparative manner as the accelerations: reference frame and 10% supplemental general level of damping (Fig. 36), reference frame and 15% supplemental damping (Fig. 37) and reference frame and 20% supplemental damping (Fig. 38). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements via SPEC's as follows: reference frame and 10% supplemental general level of damping (Fig. 39), reference frame and 15% supplemental damping (Fig. 40) and reference frame and 20% supplemental damping (Fig. 41).

Similar analyses have been carried out in the case of 15 stories frame. The results associated to 15 stories frame are presented below: reference frame and 10% supplemental general level of damping (Fig. 42), reference frame and 15% supplemental damping (Fig. 43) and reference frame and 20% supplemental damping (Fig. 44). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements: reference frame and 10% supplemental general level of damping (Fig. 45), reference frame and 15% supplemental damping (Fig. 46) and reference frame and 20% supplemental damping (Fig. 47).

The proposed SPEC's are presented in the same comparative manner as the displacements: reference frame and 10% supplemental general level of damping (Fig. 48), reference frame and 15% supplemental damping (Fig. 49) and reference frame and 20% supplemental damping (Fig. 50). The frames acted upon by sinusoidal acceleration exhibit their seismic responses in top lateral displacements via SPEC's as follows: reference frame and 10% supplemental general level of damping (Fig. 51), reference frame and 15% supplemental damping (Fig. 52) and reference frame and 20% supplemental damping (Fig. 53).

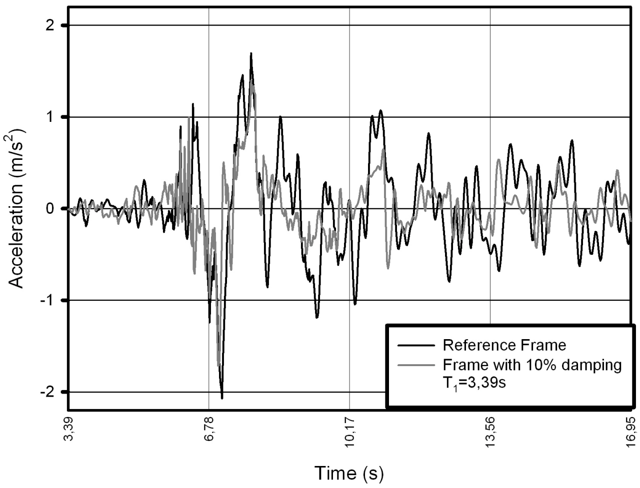

Fig. 42 Acceleration - reference frame versus frame with 10% damping (VRANCEA)

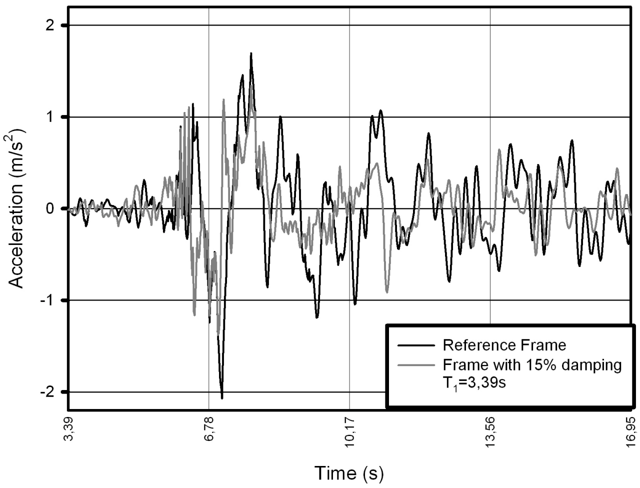

Fig. 43 Acceleration - reference frame versus frame with 15% damping (VRANCEA)

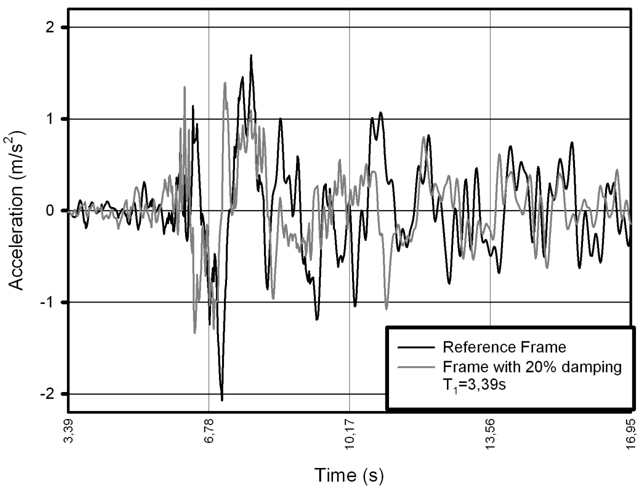

Fig. 44 Acceleration - reference frame versus frame with 20% damping (VRANCEA)

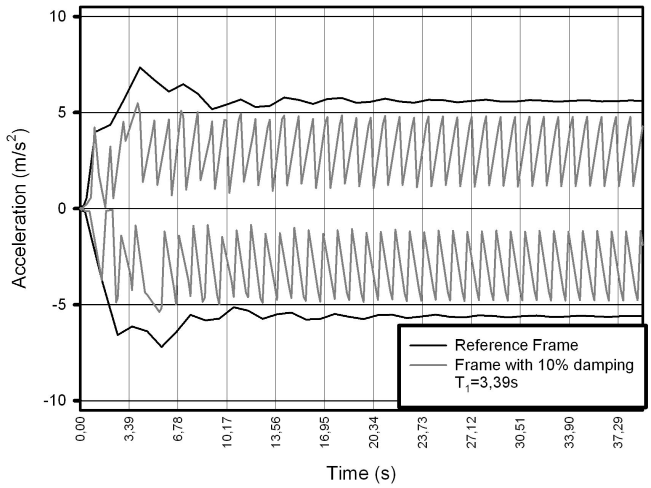

Fig. 45 Acceleration - reference frame versus frame with 10% damping (Sinusoidal)

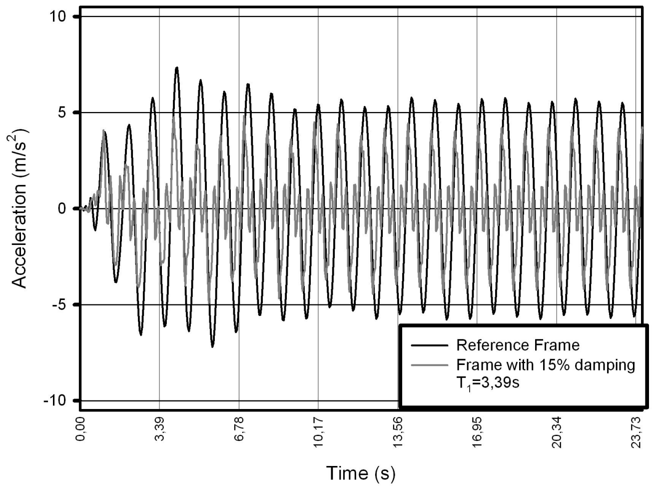

Fig. 46 Acceleration - reference frame versus frame with 15% damping (Sinusoidal)

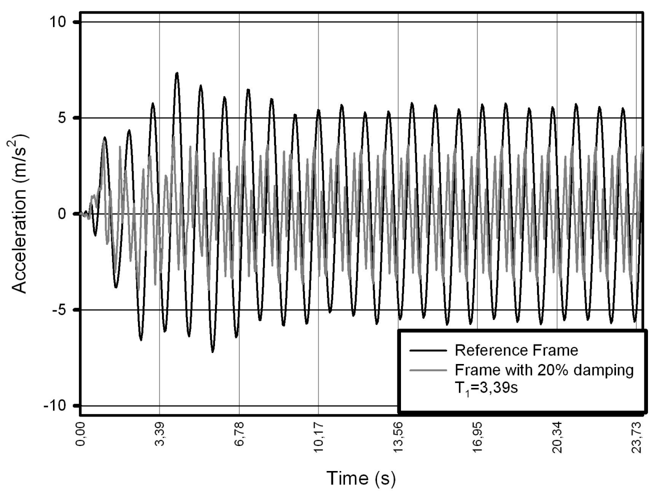

Fig. 47 Acceleration - reference frame versus frame with 20% damping (Sinusoidal)

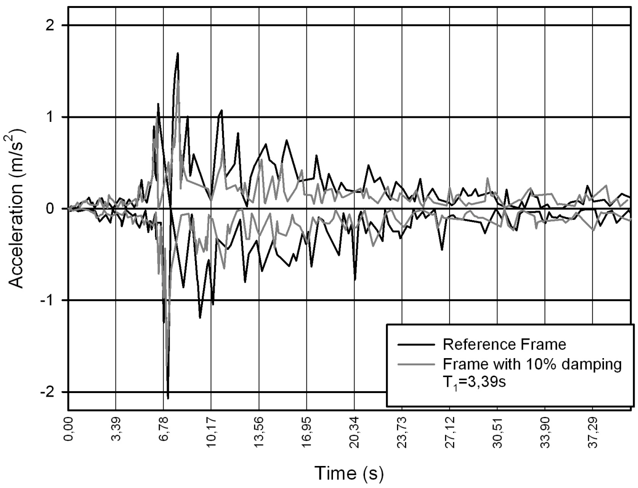

Fig. 48 Acceleration mitigation curves - reference frame versus frame with 10% damping (VRANCEA)

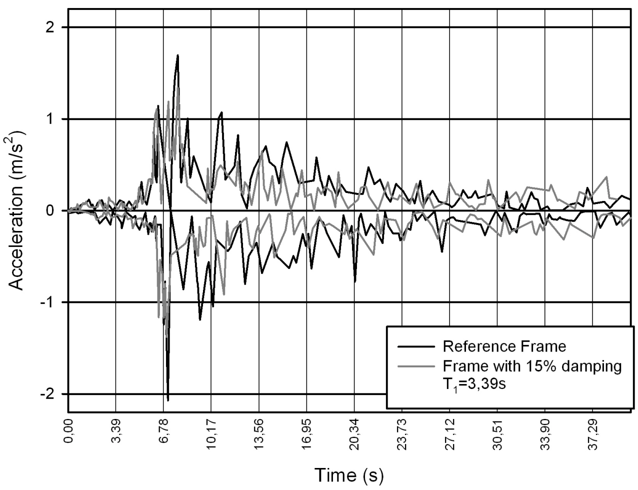

Fig. 49 Acceleration mitigation curves - reference frame versus frame with 15% damping (VRANCEA)

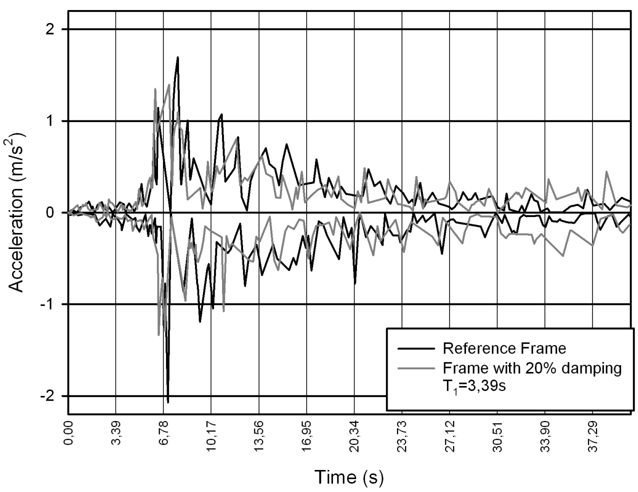

Fig. 50 Acceleration mitigation curves - reference frame versus frame with 20% damping (VRANCEA)

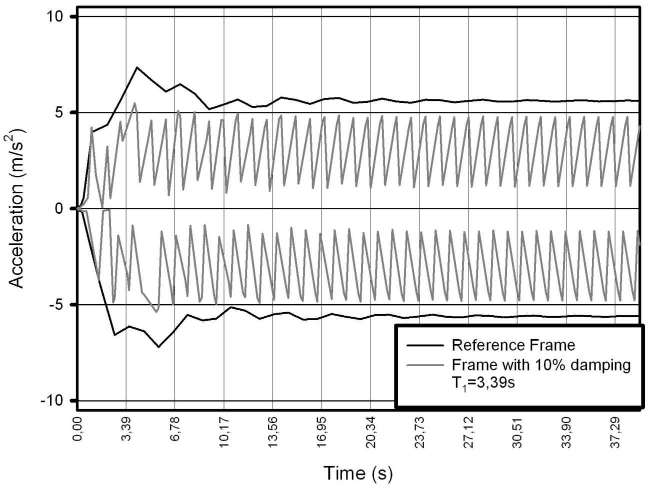

Fig. 51 Acceleration mitigation curves - reference frame versus frame with 10% damping (sinusoidal)

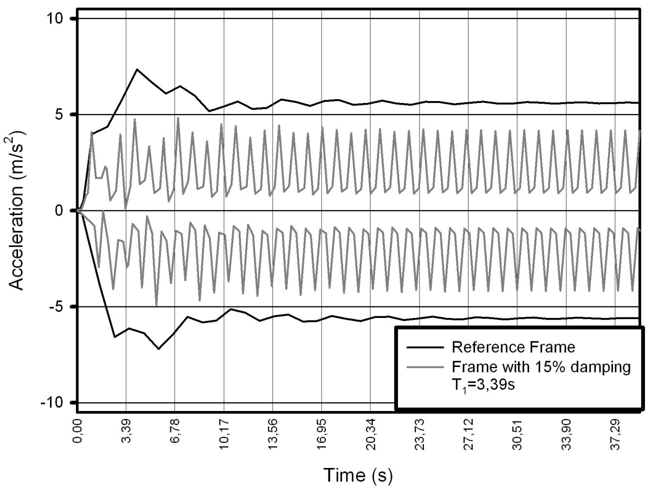

Fig. 52 Acceleration mitigation curves - reference frame versus frame with 15% damping (sinusoidal)

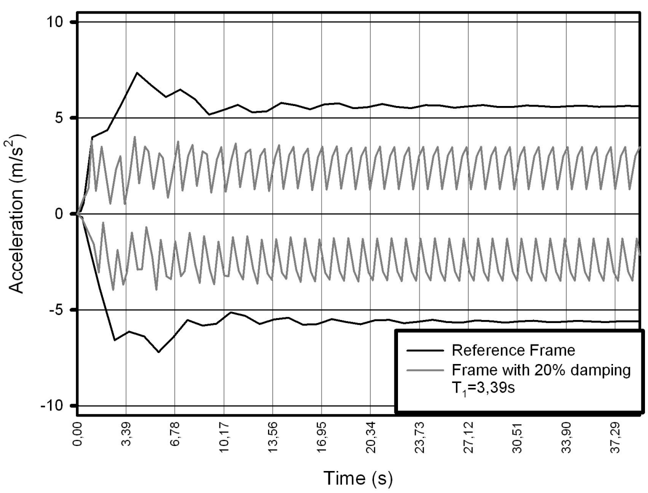

Fig. 53 Acceleration mitigation curves - reference frame versus frame with 20% damping (sinusoidal)

Eloquent conclusions may be inferred from the efficiency of added damping versus number of stories. For this, a number of 4 sets of 6 stories, 9 stories, 12 stories and 15 stories, respectively have been analyzed. Indeed, it may be concluded that in the case of high-rise structures, reduction in lateral displacements decrease versus the case of structures with less that 12 to 15 stories. This tendency appears to preserve no matter the global level of damping.

Due to the total asymmetry of seismic action, the reduction in lateral displacements has been analyzed in terms of their both, positive and negative values of top lateral displacements. Associated numerical results are presented in figures 54 to 61.

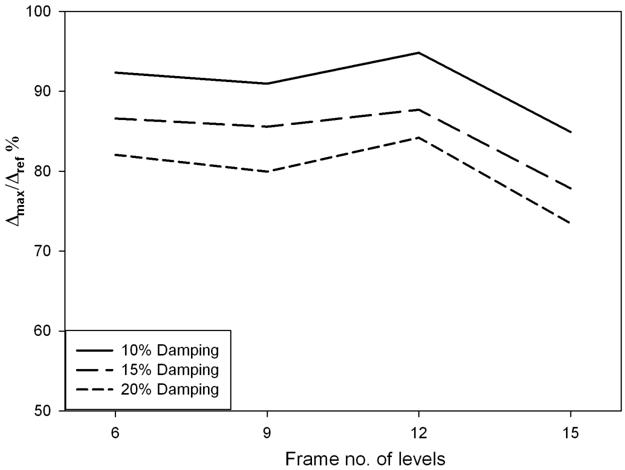

Fig. 54 Damping reduction curves negative values (VRANCEA)

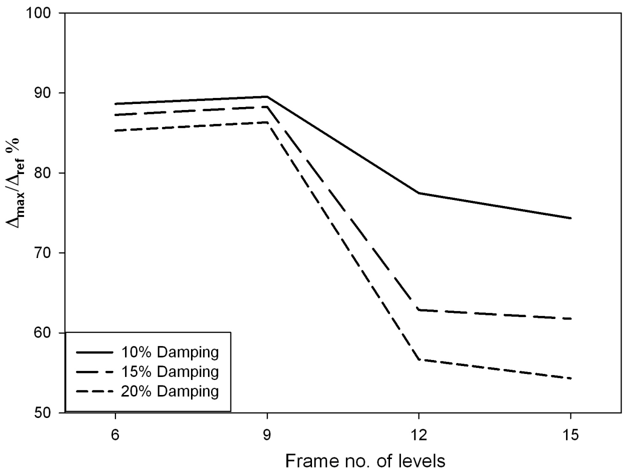

Fig. 55 Damping reduction curves positive values (VRANCEA)

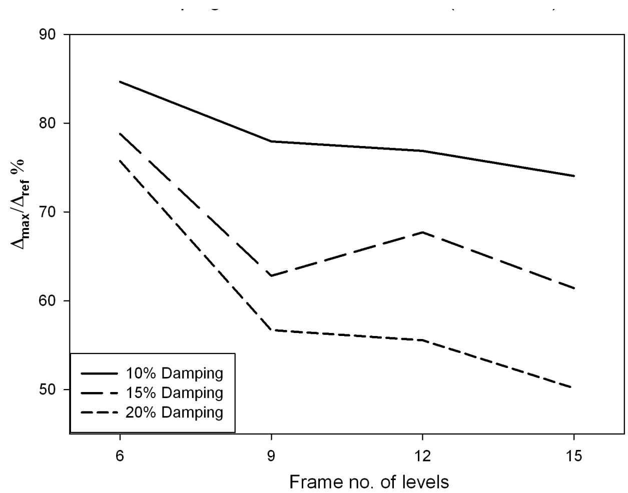

Fig. 56 Damping reduction curves negative values (sinusoidal)

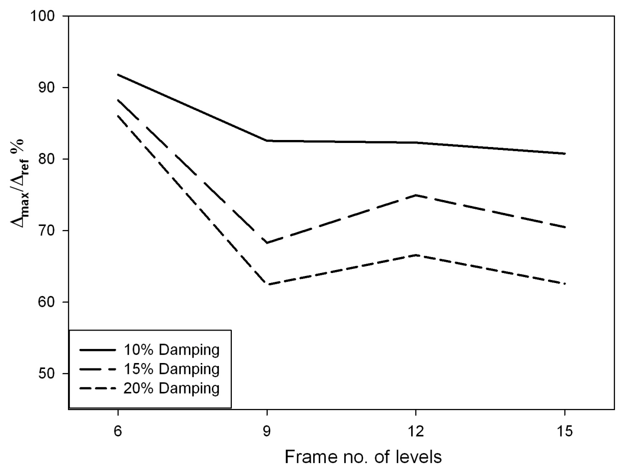

Fig. 57 Damping reduction curves positive values (sinusoidal)

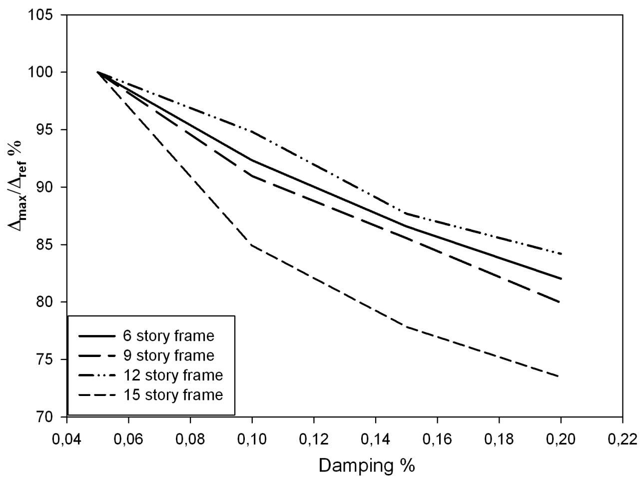

Fig. 58 Damping reduction curves negative values (VRANCEA)

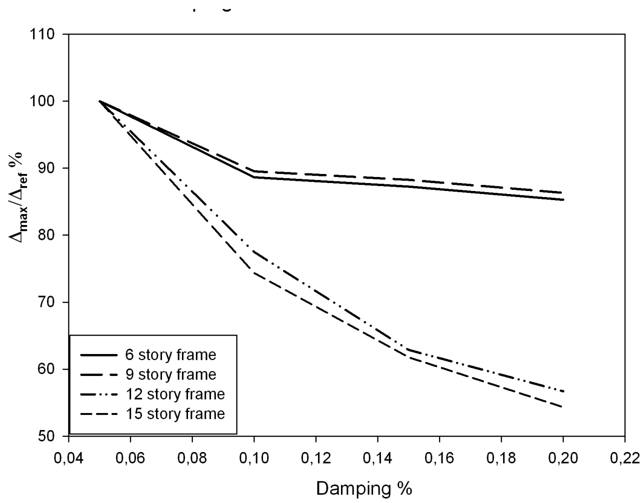

Fig. 59 Damping reduction curves positive values (VRANCEA)

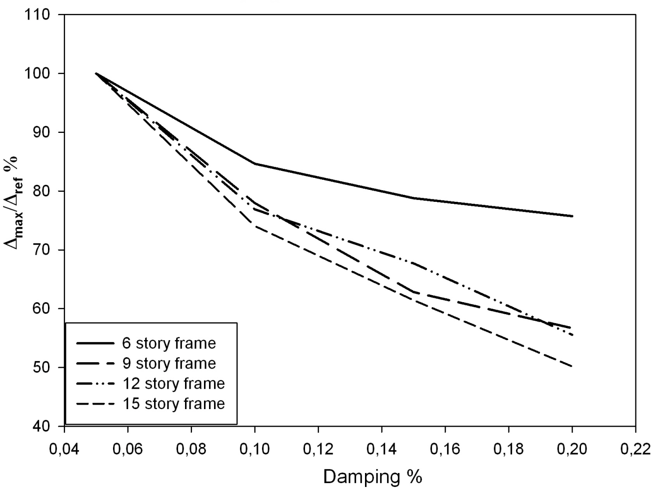

Fig. 60 Damping reduction curves negative values (sinusoidal)

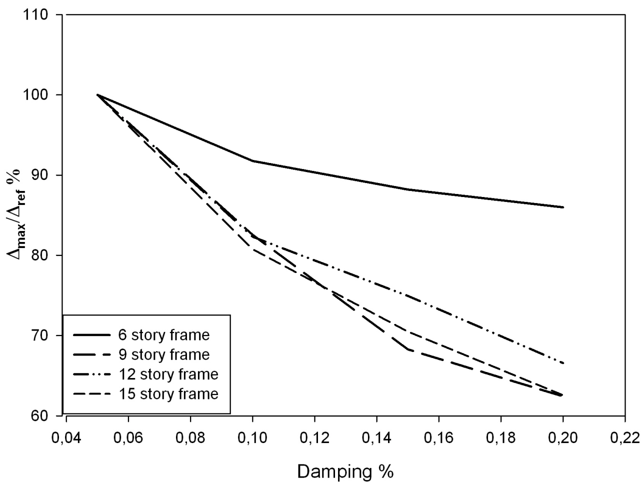

Fig. 61 Damping reduction curves positive values (sinusoidal)

4 Conclusions

Literature associated to seismic devices aiming at mitigating seismic structural response [11], [12], [13], [14] focuses on the efficiency of proposed techniques with reference to both, induced displacements and accelerations.

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 [8] 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.

4.1 Remarks regarding SPEC's associated to displacements

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 12 story frame, the length of the mitigation interval is reduced from $7T_1$ to $3T_1$ in the case of 10% added damping and Vrancea accelerogram, (Fig. 12). Similarly, SPEC's associated to 15% and 20% levels of added damping are, also, computed (Fig. 13, Fig. 14). Associated results for the sinusoidal type excitations are presented in the same manner: in the case of 10% supplemental damping (Fig. 15), in the case of 15% added damping (Fig. 16) and in the case of 20%, respectively (Fig. 17).

4.2 Remarks regarding SPEC's associated to accelerations

Regarding the efficiency of passive protection via viscous damper – expressed in induced accelerations of lateral motion of top level - it may be concluded that the damping level do not affect the values of induced accelerations. The accelerations are, in fact, related to the statically equivalent seismic forces and the seismic forces (seismic base shear) do not depend on, not do they change in any way with the amount of damping the structure is provided with.

What does, nevertheless, the damping level change in induced accelerations? It shortens the time interval of transitory (seismically induced) vibratory motion. This effect is of real importance in seismically induced structural vibrations. Multi-storey steel structures may undertake quite large lateral displacements without dramatic effect in its stress state, while an alternative (vibratory) motion associated with even smaller lateral displacements will significantly affect this state.

The mitigation envelope curves (acc. SPEC's) are, also, very suggestive in terms of the length of the interval expressed in fundamental period of structural vibrations. In the case of reference frame, the length of the mitigation interval is reduced from 4.5T1 to 2.5T1 in the case of 10% added damping and Vrancea accelerogram (Fig. 30). Similarly, the mitigation curves associated to the other levels (15% and 20%) of added damping and for the case of sinusoidal excitation are presented: a reduction to 2T1 in the case of 15% damping level (Fig. 31), a reduction to 1.5T1 (Fig. 32) for 20% damping level versus reference 5%. In the case of sinusoidal input accelerogram, reduction in the length of mitigation interval (from 5T1 – in the case of reference frame) is down to 4T1, for 10% damping level (Fig. 33), down to 3.5T1, for 15% damping level (Fig. 34) and down to 2.5T1, in the case of 20% damping level (Fig. 35).

4.3 General conclusions

In what regards proposed mitigation enveloped curves, they prove to be a direct tool of assessing the efficiency of supplemental damping. Their expressing in terms of fundamental period of the structure allows a rapid and synthetic evaluation of supplemental damping efficiency. As it has been pointed out, if the structure vibrates at peak values of its kinematical parameters, incipient or even full shakedown type behaviour is induced. A vibration "stage" along a time interval up to two fundamental periods (2T1) will save the structure of shakedown behaviour and, consequently, of remanent deformations. Also, the decrease in the values of associated parameter (top lateral displacements in this study) offers immediate asses of the measure of reductions in these values.

Finally, it may be emphasized that the versatility of mitigation envelope curves and their synthetic feature opens the possibility of incorporating them in the set of performance criteria of seismically protected (via viscous dampers) steel structures.

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