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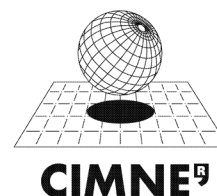
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Prestress Accumulation - Release for Damping of Impact-Borne Vibrations. Numerical Analysis of Simple Frame Structures.

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Abstract

In this paper a numerical study is presented, which tailors so-called Prestress Accumulation-Release (PAR) Strategy to mitigate free vibrations of frame structures. First, the concept of proposed semi-active technique is outlined and possible applications are specified. In the second part of the work a parametric study is discussed, which illustrates the potential of the method for mitigation of free vibrations induced by impact or other initial load scenarios. Special attention is given to the energy balance including all relevant contributions to the total energy of the considered dissipative system. The proposed technique shows a very high potential in mitigation of free vibrations, exceeding 99% of the reference amplitude after 5 cycles of vibration.

I. INTRODUCTION

A. Problem outline

Some engineering structures are exposed to transient dynamic loading which, although not dangerous for the structure itself, may generate harmful or undesirable effects. It has been therefore an engineering problem to eliminate vibrations induced by non-destructive impacts, force impulses generated by working machinery, etc. Effective mitigation of such vibration might for example help improve the resolution of optical equipment or reduce the noise generated by vibrating structure. Out of three classes of possible solutions, i.e. passive, active and semi-active, there has been a growing attention to the semi-active methods which allow for adjusting some mechanical parameter characteristic on one hand, and utilise the structural deformation to introduce control forces – on the other hand. One advantage of the latter feature, which is common with passive devices, is that the system does not require external power to directly generate the control forces. The external power is needed to regulate an actuator which in turn changes the magnitude of the control force according to the control unit algorithm and is typically in the order of magnitude of tens of Watts. Symans and Constantinou in [10] give definitions of all three classes of methods and provide a review of semi-active solutions for seismic protection of structures. In particular a reference is given to a stiffness control device introduced by Kobori et al. [6], where bracing of a frame structure is locked or unlocked in order to keep the structural response at lowest possible level during an earthquake. Also, the design assures that in the power failure situation the structure works with maximum stiffness, i.e. with the bracing locked.

Among many available concepts of tailoring semi-active techniques to mitigate vibration, work [2] give interesting example of coupling structural response with PZT actuators and [4] present adaptive pneumatic fenders to optimally decelerate ship impact. Another concept is investigated in [7], where a mass-spring system vibrations are suppressed due to a controlled detaching and reattaching of a spring, whereas [5] deals with the use of on-off rod connections control for energy dissipation in a flexible truss-beam structure. In the present work another semi-active technique is analysed which aims at mitigation of free vibrations. Its efficiency is demonstrated numerically on an example frame structure.

B. Prestress Accumulation – Release (PAR) Strategy as a semi-active technique

In the PAR strategy it is assumed that a structure undergoes free vibrations and that there is a certain device or devices installed in the structure capable of imposing kinematic constraints on some degrees of freedom of the system. For instance, a layered beam could be equipped with a device that allows or constrains the relative slip between layers, or a system composed of masses and springs is equipped with a device which releases or reattaches a chosen spring to a mass. Given such devices are in place, the strain accumulated in the structure could locally be released which results in conversion of a part of the strain energy to the kinetic energy of local, higher frequency vibrations. In the next phase constraints are reimposed which results in "freezing" of a part of the deformation. Local, higher frequency vibrations introduced after reimposing of the constraints can be effectively damped out with material damping. If the time instant of reimposing constraints is chosen properly, i.e. at the moment of maximum relative dislocation between top and bottom beam, it will introduce a prestress in the structure. It should be emphasised at this point that a relatively small energy was used to adjust the actuator device, f.e. a piezo actuator that controls the friction in a joint (like one introduced by Gaul [3]) and in turn a control force was generated in the structure that is a result of the structural motion itself. Furthermore the generated prestress acts in the direction that opposes the movement of the structure. As mentioned in [10] such a behaviour is desirable for many semi-active techniques because it promotes the stability of the system. Obtained prestressed structure, with a new equilibrium configuration, could

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then return to the initial state by means of a gradual, quasi-static release of the prestress accompanied by the frictional dissipation in the contact surfaces. For many practical cases the above procedure needs to be repeated until the desired effect is obtained. As a result a very high potential in the mitigation of the fundamental mode of vibrations is achieved.

II. NUMERICAL MODEL

A. Introduction

Some numerical as well as experimental results of application of the PAR technique to layered beams can by found in [9], where on-off control was applied to adjust relative movement of adjacent structural layers. In the present study a frictional joint is assumed in the nodes of a frame structure allowing for continuous adjustment of the moment bearing capability of active nodes. For demonstrative purposes the assumed frame ends with a hinge with a panel attached to it (cf. Fig. 1). In the simulations the panel opens according to a prescribed angular velocity profile. Panel opening is initiated with a micro blast located at the end of the main structure. Both the micro blast force and step changes in the panel opening angular velocity are the sources for the free vibrations of the structure which are then subject for mitigation with PAR technique.

B. Assumed model of a frame cantilever with active nodes

Physical model analysed in numerical simulations was a one meter long cantilever beam comprising two layers 0.1 m apart and connecting elements spaced every 0.1 m. Two frictional joints at both ends of each connecting element (depicted in green in Fig. 1) governed the rotation in the node about the X3 axis. Active frictional joints allowed for continuous, controlled adjustment of the normal force between the frictional surfaces, thus allowing for adjusting friction between the adjacent surfaces. This, in turn, allowed for the smooth transition between frame nodes and truss nodes. Frame mode of an active node corresponds to a maximum normal force applied to the frictional surfaces and consequently no slip between these surfaces within the design range of bending moments, whereas the truss mode corresponds to minimum normal force and consequently negligible moment bearing capability in the nodes.
All cantilever members were modelled as steel, prismatic, rectangular bars with cross-section of 20x6 mm.
There are two physical sources of energy dissipation in the assumed model:
1) material damping,
2) friction between surfaces of active nodes.
Ad. 1) Rayleigh damping model was assumed, taking the form: $[C] = \alpha[M] + \beta[K]$, with mass and stiffness coefficients respectively $\alpha = 1.0e - 6$ and $\beta = 1.0e - 5$.
Ad. 2) Coulomb friction model in accordance with [1] was utilised with the slip condition: $\Phi =\mid M_t \mid -\mu M_n \leq 0$, where M_n is the generalized force produced due to the contact, M_t stands for tangential traction carried by the contacting surfaces and μM_n is the maximum shear before slip occurs. The coefficient of friction $\mu = 0.1$ was assumed in the simulations. The value of M_n was adjusted according to the algorithm defined in a user subroutine and outlined in Fig. 2.

C. Proposed control strategy

In the outline of the control strategy presented in Fig. 2 the control procedure begins with the structure working in the frame mode, i.e. there is maximum friction generating moment M_n applied in the nodes. If the maximum deflection of the oscillatory movement at the cantilever tip is detected then the applied moment drops to zero and thus the transition of the nodes to the truss mode occurs. It results in the longitudinal dislocation of the two main layers in direction $X1$. Now, control algorithm awaits for the detection of the maximum displacement of layers in X1 direction in order to increase the M_n to maximum again. If the simulation was terminated at this point, the structure would come to a new equilibrium position, which differs from the original one. It is however desired for the structure to come back to the original state. Therefore the M_n is gradually decreased, allowing for limited slip between the contact surfaces, which in turn results in quasi-static return of the structure to the original configuration. In this phase the value of M_n is decreased by few percent if there is no slip between contact surfaces or is kept without change, otherwise. Finally, the maximum value for the M_n is restored,
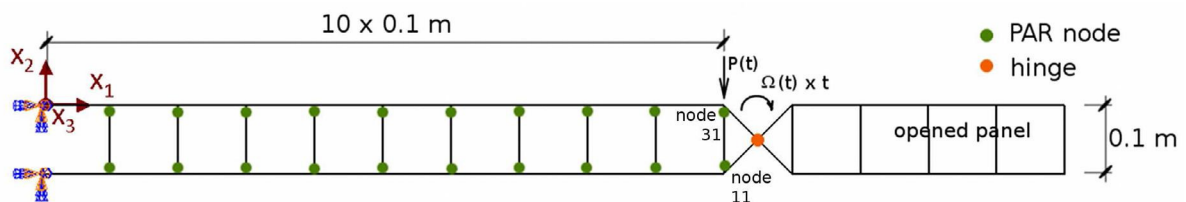

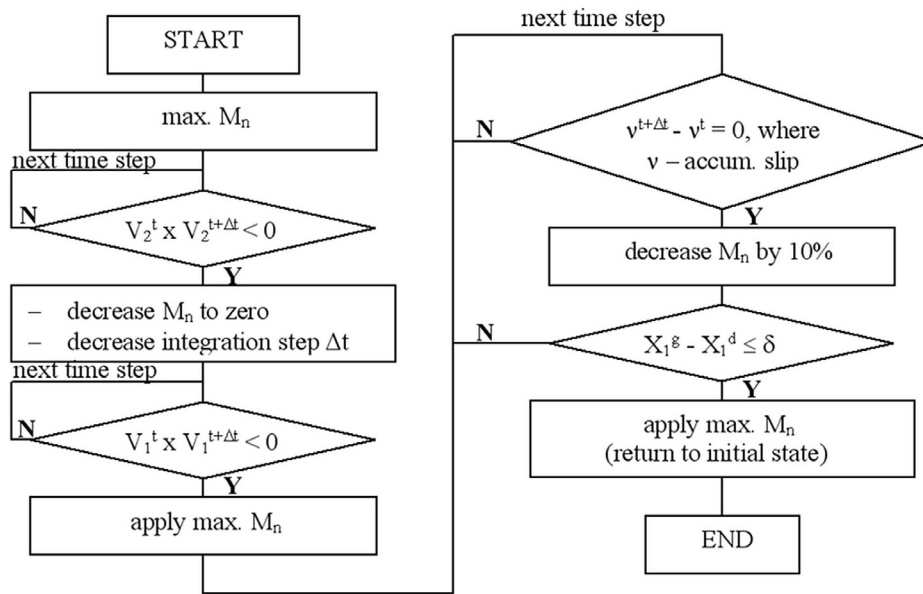Fig. 1.   Structure assumed in the simulations (active nodes depicted in green).

Fig. 2. Control strategy outline.

provided that the structure is sufficiently close to the initial configuration. This condition can be monitored f.e. with relative displacement of tips of top and bottom beam in $X1$ direction.

The control strategy could be summarised as follows:

Phase 1. Upon detection of maximum displacement amplitude trigger the sequence of active nodes transition from frame to truss and, after a very short period of time, back to frame mode.

Phase 2. Gradually release the friction generating moment and monitor the structure return to the initial configuration.

Phase 3. Restore the full stiffness and go back to Phase 1, if needed.

III. RESULTS OF SIMULATIONS

A. Introduction

Numerical simulations were carried out with Abaqus/Standard Finite Element Software using finite displacement theory because of large rotations during opening of the panel. Active nodes were modelled with connector elements in which the available component of relative motion was the rotation about $X3$ axis with frictional behaviour defined. Nonlinear behaviour of the active nodes was introduced as the friction generating force was a nonlinear function of a control variable updated in a feedback loop via a Fortran user subroutine.

The fundamental mode of vibration of the assumed model with the opened panel was:

- 19.6 Hz for structure with frame nodes,
- 3.96 Hz for structure with truss nodes.

The first longitudinal eigen frequency was 1213.4 and 1186.8 Hz, respectively.

B. Response of the system with all nodes active

In the initial simulation all active nodes (indicated by green spots in Fig. 1) were activated. The vertical displacement of the cantilever tip is depicted in Fig. 3. As can be seen switching active nodes from frame mode to truss and back qualitatively changes the behaviour of the vibrating structure. The prestress is then gradually unloaded which results in slow return to the base state. The same process is shown in Fig. 4 in terms of the accumulated slip between the frictional surfaces. A step change in the slip is triggered with the friction generating moment reduced to zero for a very short period of time. The remaining slip is accumulated during gradual decrease of the friction generating moment. During this phase active nodes are in the transition state between frame and truss. Sufficient unloading of the prestress triggers the return of active nodes to the frame mode. Then the whole procedure may be repeated if needed. In the shown example 90.4% of the vibration amplitude was mitigated after time period corresponding to 5 cycles of vibration. Accordingly, after 13 cycles of vibration 99.6% of the amplitude was mitigated.

The longitudinal displacements of the top and bottom layer's tip are shown in Fig. 5. Switching to truss mode and back
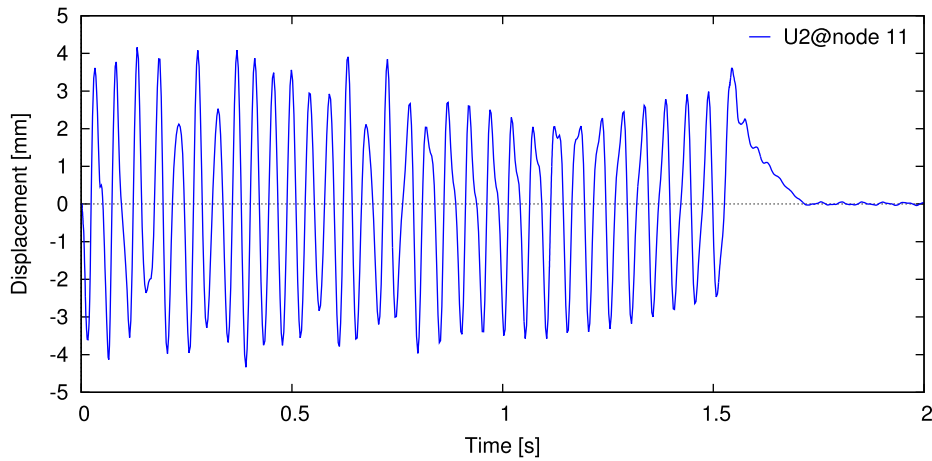
Fig. 3. Vertical displacement at the tip of main structure (node No 11).

introduces higher frequency vibrations which correspond to the identified longitudinal eigen mode. These vibrations are effectively damped out with material damping.

For this particular case the nodes are switched at the point of maximum $+X2$ displacement. Switching to truss mode results in top beam tip (node No 31) travelling in $+X1$ direction, whereas bottom beam tip (node No 11) travelling in $-X1$ direction (cf. Fig. 5b)) which, after switching back to frame mode, introduces a prestress in both beams (cf. Fig. 6). Vertical lines in Fig. 5b) refer to switching from frame to truss mode and back from truss to frame, respectively.

C. Energy balance

The sum of mechanical energy of the system, energy dissipated and the work of external forces done on the structure must remain constant throughout the process. For the analysed system undergoing free vibrations there are following non-zero components of the total energy balance:

- kinetic energy,
- strain energy,
- energy dissipated in viscous processes, including material damping,
- frictional dissipation at contact surfaces of active nodes.

All of the above contributions are depicted in Fig. 7. It can be observed that the primary source for energy dissipation is the material damping of higher frequency vibrations introduced with the activation of nodes. Frictional dissipation also contributes to the system balance, however to a smaller extent. If the amount of dissipation since activation of nodes was
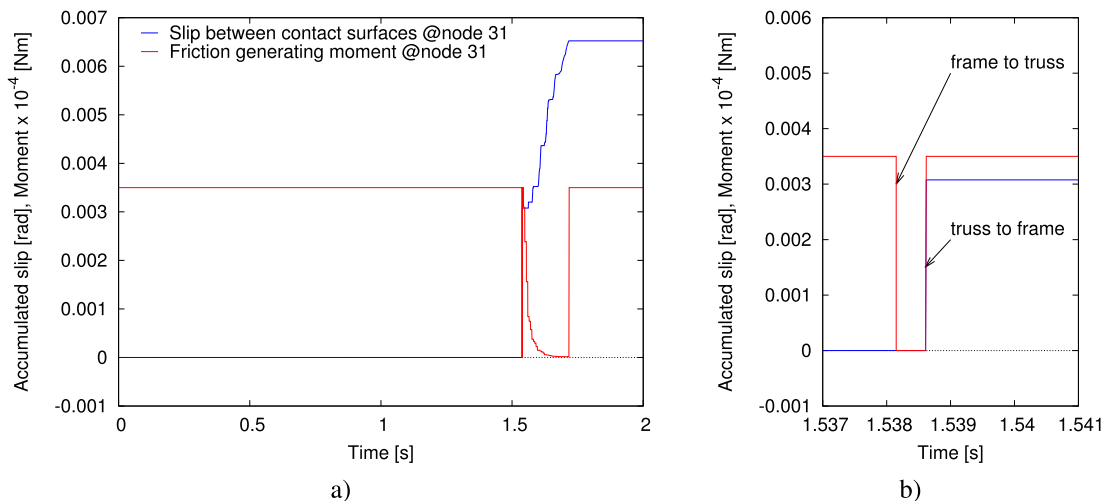

Fig. 4. Accumulated slip between contact surfaces and the actuator moment: a) full time history; b) time window where zero moment corresponds to the truss mode.
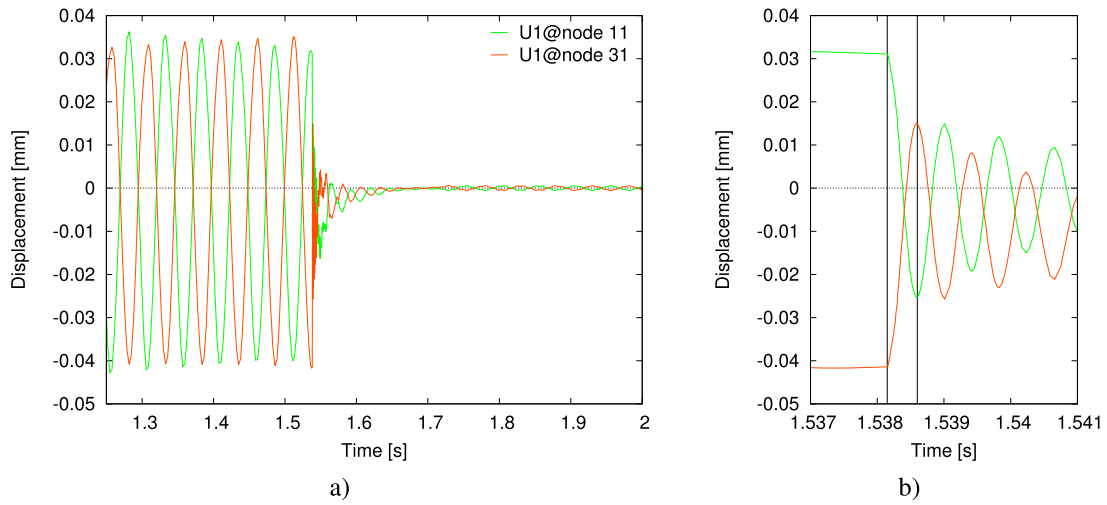
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Fig. 5. Horizontal displacement of tips of top (node No 31) and bottom (node No 11) layers: a) full time history; b) longitudinal vibrations triggered with nodes activation.

considered then 84% belonged to material damping and 16% belonged to frictional dissipation. A slight decrease in the total energy balance can also be observed. This is because there is additional dissipation, not associated with any physical process but with the Hilber-Hughes numerical integration scheme of the equations of motion. For the analysed example the amount of numerical damping introduced between the time instant just before the nodes activation and the end of simulation was 1.8%.

IV. PARAMETRIC STUDY

Based on the carried out initial simulations the following parameters have been identified to have an important impact on the system performance:

1) material damping,
2) number of active nodes,
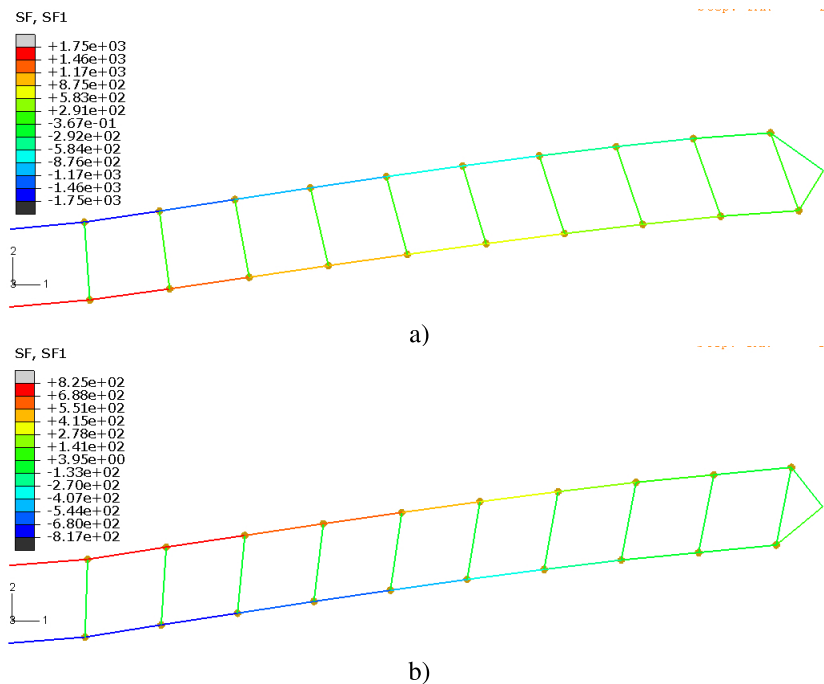3) amount of decrease in the friction generating moment in phase 2.

Fig. 6. Axial force in beam elements a) before and b) after switching from frame to truss mode and back. Deformation scale U1x500, U2x40 (opened panel not shown).
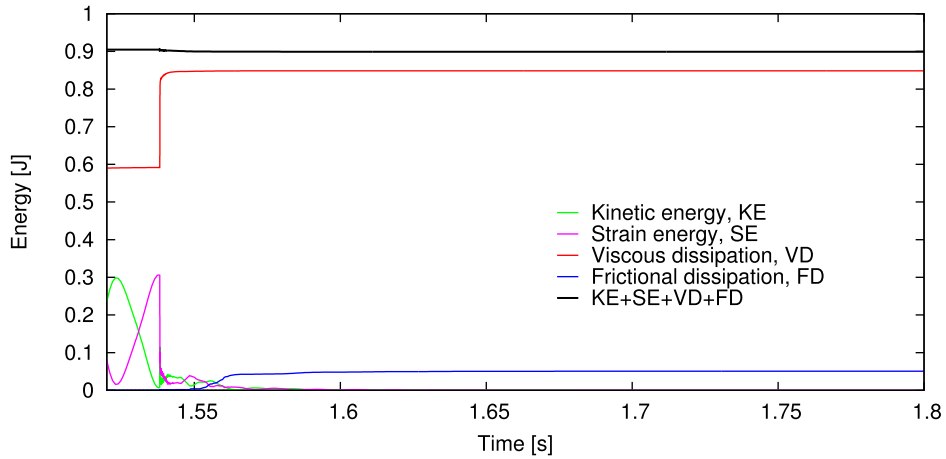
Fig. 7.   Energy balance of the whole system.

A. Material and numerical damping

First, the influence of numerical damping on the solution needs to be analysed. According to [1] in the implicit integration of equations of motion a slight numerical damping is introduced as an additional parameter in Hilber-Hughes-Taylor algorithm. For most cases the value of $\alpha_{HH} = -0.05$ is a good choice. However, in order to verify that the efficiency of the proposed solution is not significantly affected with the numerical damping, values of α_{HH} increased by 50% and 100% with respect to the default value were also analysed. Results shown in Fig. 8 indicate that the increased value of numerical damping affects the time evolution of the solution, it does not however improve the overall efficiency. On the other hand too little numerical damping results in too much numerical noise in the solution which affects the control algorithm and thus also the global response. Decreasing α_{HH} should therefore be avoided (cf. red curve in Fig. 8).

As mentioned before, mass and stiffness proportional damping coefficients of the Rayleigh model are $\alpha = 1.0e - 6$ and $\beta = 1.0e - 5$ respectively. According to a well known formula for modal damping coefficient ξ_i corresponding to i–th eigenmode:

$$\xi_i = \frac{\alpha}{\omega_i} + 2\beta\omega_i, \tag{1}$$

damping of the 1st bending mode and the first antisymmetric longitudinal mode is equal to $\xi_5 = 0.2\%$ and $\xi_{34} = 15.2\%$, respectively. Thus, assumed damping coefficients provide slight damping of the main oscillatory movement of the structure, while introducing substantial damping of the higher frequency vibrations generated after phase 1. In another simulation a coefficient β, which has more impact on higher frequency damping, has been decreased by factor of 10. This gives $\xi_5 = 0.02\%$ and $\xi_{34} = 1.52\%$. Based on the results shown in Fig. 9b) it can be concluded that if damping is decreased, it takes more time for the higher frequency vibrations to be ceased, but in both cases energy dissipated with material damping
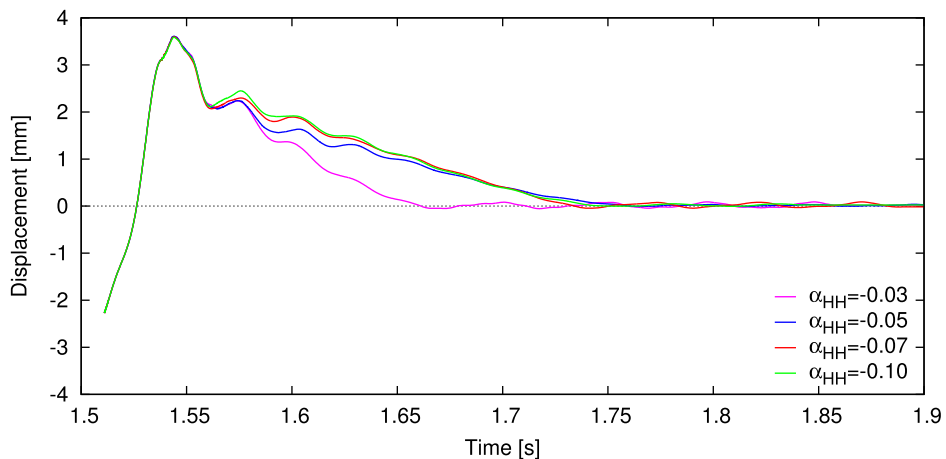

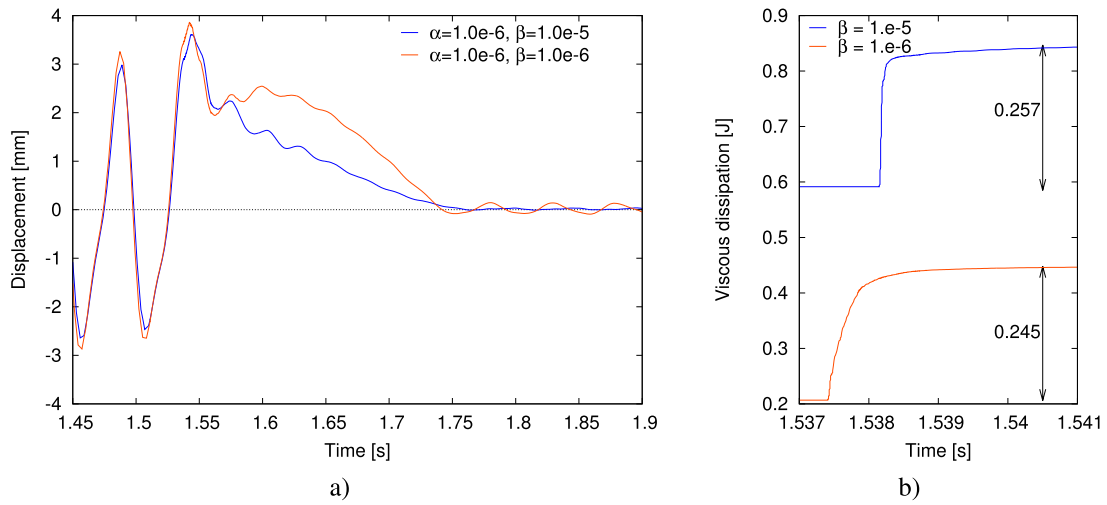Fig. 8.   Influence of numerical damping on the solution.

Fig. 9. Influence of decrease of stiffness proportional damping: a) in terms of vertical displacement of the bottom beam tip (node No 11); b) in terms of viscous dissipation during phase 1.

is similar (4.3% difference in analysed cases). The overall mitigation of vertical displacement amplitude is also comparable (cf. Fig. 9a)) amounting to 96.5% after time period of 13 cycles of reference vibration.

B. Number of active nodes

Preceding results have been obtained with all active nodes connecting top and bottom beam. In this section the number of active nodes is reduced. Namely, starting from the fixed support, only 1, 3 or 7 pairs of nodes were active, while the remaining ones were kept as passive frame connections (cf. Fig. 10b)). In these cases not all the stress accumulated in top and bottom layers could be released with activation of nodes and thus less energy could be transferred to the longitudinal vibration of top and bottom layers. As a consequence the control algorithm needed to activate nodes transition more then once in order to obtain the desired effect (cf. Fig. 10a)). Nevertheless, in all considered cases, except the case with one pair of active nodes, more then 90% of amplitude mitigation was obtained. Comparison of the vertical displacement amplitude mitigation after 5 cycles of reference vibration is shown in Table I.

TABLE I
VERTICAL DISPLACEMENT AMPLITUDE MITIGATION WITH VARYING NUMBER OF ACTIVE NODES.

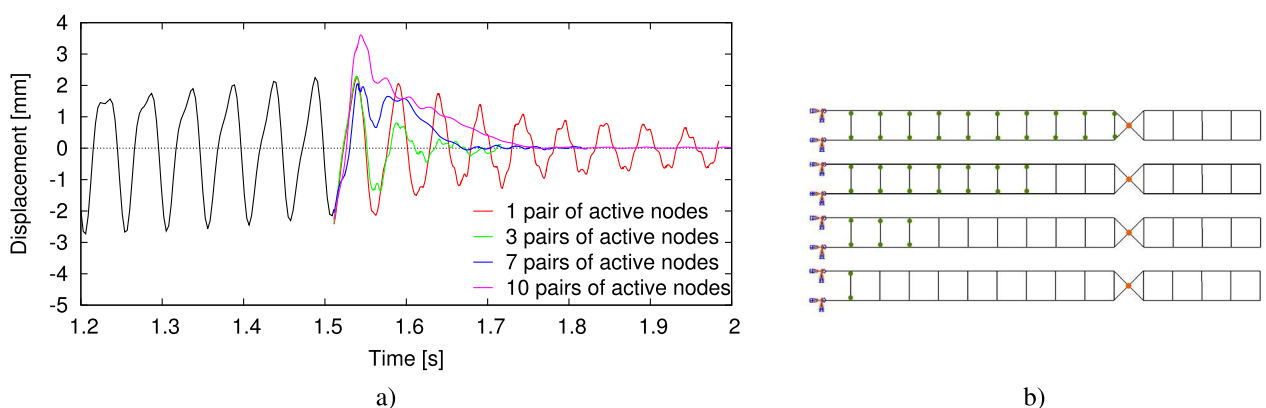| Number of active nodes	vertical amplitude reduction	number of node activations
10	99.4%	1
7	98.3%	2
3	90.8%	6
1	56.7%	9

Fig. 10. Varying number of active nodes: a) vertical displacement at node 11; b) 10, 7, 3 and 1 pair of active nodes location.

C. Amount of decrease in the friction generating moment in phase 2.

As indicated in Fig. 2 in the second phase of the process the prestress introduced into the structure is gradually unloaded by means of decreasing friction in active nodes. This can be done slowly resulting in a quasi-static return of the system to the base state, or more rapidly. In the first case the final effect in terms of mitigated amplitude of vertical displacement is more pronounced, but it takes much more time, i.e. the structure works with reduced stiffness for longer time. In the second case the mitigation is fast, but some left-over vibration is introduced when the full stiffness is restored (cf. Fig. 11). In an additional case the maximum value of M_n is preserved throughout the whole simulation which corresponds to oscillation about a new equilibrium position (cf. black line in Fig. 11).

In Tab. II results are compared in terms of the efficiency of the vertical displacement mitigation after 5 and 13 cycles of reference vibration. Each row corresponds to a simulation with different value of M_n decrease upon detecting a time increment without slip between contact surfaces. Note that results presented in Fig. 11 and in Tab. II refer to a single activation of nodes.

TABLE II

AMPLITUDE MITIGATION OBTAINED WITH DIFFERENT VALUES OF FRICTION GENERATING MOMENT DECREASE IN PHASE 2.

% of M_n reduction	% of amplitude reduction after	
	5 cycles of vibration	13 cycles of vibration
5.0%	61.9%	71.6%
6.0%	73.2%	81.3%
7.5%	96.2%	99.4%
10.0%	99.1%	99.2%
11.5%	98.5%	98.3%
20.0%	96.3%	96.4%

V. DISCUSSION

In this paper a method for semi-active mitigation of free vibrations has been presented. In the so-called PAR strategy, the strain energy accumulated in the system during vibration is transferred to kinetic energy of higher frequency, longitudinal vibrations of the structural members and eventually efficiently dissipated with material dissipation. In addition PAR strategy introduces an elastic control force into the structure which acts in direction opposing the movement. This prestress acts as a braking force to the vibration. Energy accumulated in prestress is gradually dissipated in the second phase of the control procedure with frictional joints of active nodes. The efficiency of this approach has been demonstrated on a case study of a frame structure. Generally the efficiency is very high, although it depends strongly on the number of active nodes installed in the structure. With few active nodes installed it takes more activations of the nodes to obtain the desired effect, whereas if all nodes are active only a single activation suffice. It has also been shown that the global response is dependent on the algorithm of applying the normal force in the frictional connections. Therefore, apart from the simple on-off strategy for applying the contact force in active nodes, also other strategies are possible, based on the feedback with the slip between contact surfaces.

Generally the PAR strategy requires that the stiffness of the structure is temporarily reduced. Time duration of the minimum
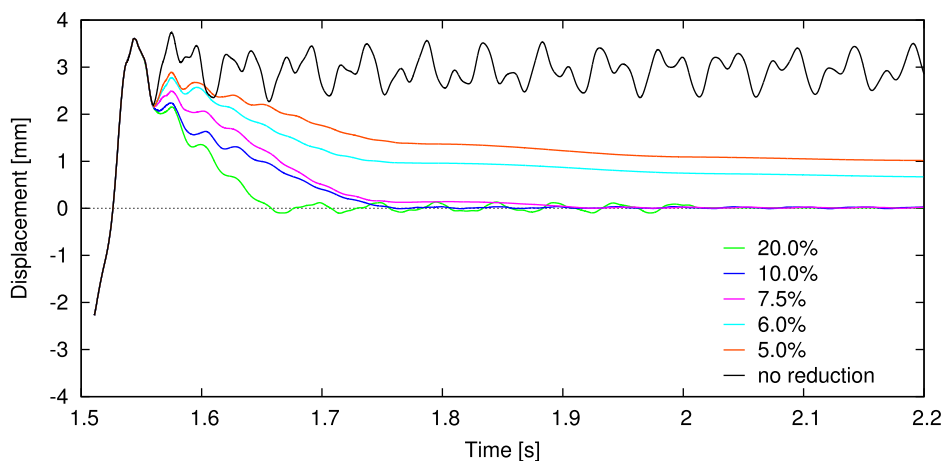

Fig. 11. Vertical displacement at node 11 for different values of M_n reduction.

stiffness mode is however very short as compared with the time of full stiffness mode.

Carried out simulations indicate some difficulties one would encounter during development of the prototype system. It seems challenging to properly reimpose the full stiffness mode since the frequency of the longitudinal vibrations is relatively high, especially as the monitoring of the relative displacement between structural elements should be avoided for the sake of simplicity. This problem however could be overcome since the frequency of the longitudinal vibration is known a priori and could be used to set the time shift of switching between two modes of the active nodes.

Another problem deals with the reliability of the structure. One possible realisation of active nodes could be based on the concept presented in [3], where a semi-active frictional joint controlled with piezoelectric actuator is described. That solution however, requires the supply voltage in order to operate in the stiff mode, which could cause problems in the situation of power failure. In a reliable active node supply voltage should reduce the stiffness, as f.e. in a patent description [8] or in a seismic protection device described in [6].

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