NUMERICAL AND EXPERIMENTAL ANALYSIS OF STRUCTURAL DAMPING FOR BOLTED SPLICE CONNECTION JOINT

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Summary: *This paper presents the finite element modeling of bolted joints for structural dynamic analysis to achieve a reasonable accuracy in simulation results. Non-linear effects in splice connected joints involve normal compressive loads holding components together combined with dynamic lateral loads inducing some amount of shear slip in contact interaction between elements of splice connection joint. The complexities of the slip process are responsible for the nonlinear nature of the interfaces, both in terms of stiffness and dissipation. Exploring the physics of joints directly is not readily done because key interactions takes place at the interface of surfaces, where instrumentation cannot be placed without changing the problem. Consequences of the specific conditions of joint connections are increased dynamic problems related to vibrations and dissipative processes in structure connection joints. Structural joints are the main reason for the significant level of energy dissipation and source of structural damping. The aim of this paper is to present some problems regarding research of structural damping and the importance of study Contact Mechanics to better understand the problem of structural damping.*

Key words*: structural damping, dynamic properties, connections joints, contact mechanic.*

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1. INTRODUCTION

The exact determination of dynamic properties of real engineering structures is a rather formidable task. There are various approximate methods to evaluate the inertia, stiffness and damping properties of a structure, of which stiffness is most determinable.

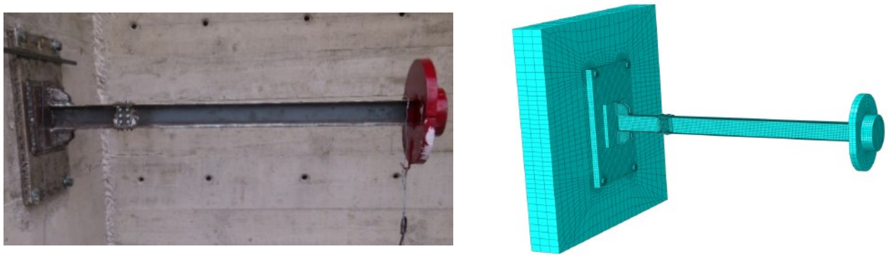

Figure 1. Experimental and numerical cantilever beam with bolted splice connection

On the other hand, the prediction of dissipative properties of a structure can be evaluated only experimentally, with a very careful and precise experimentations. The complex nature of energy dissipation process stems from the nonlinear contact interaction behavior. Effects of bolted joints of one single connection extracted and examined separately from the main structure indicate that the addition of bolted joints decreases the structure natural frequency by adding an additional mass of connection elemnts to the structure. Furthermore, the main difference and impact of the usage of bolted connection joints are that significantly increase the damping ratio. Using software such as the Abaqus and the Ansys, must be utilized for a better definition of bolt connection mechanical property and numerical parameters. It is important to remark that by using the aforementioned software, it is not possible to accurately describe the behavior of bolted connections and energy dissipation processes, because the contact interaction of the two bodies is still not fully understood. In addition to the above, we can consider Coulomb's law of friction to be exact only in certain cases.
This paper presents one part of numerical verification of experimental investigation of characteristics of bolted splice connection joint.

2. THEORY

The relationship and complexity of structural damping and contact surfaces interaction can better be comprehended if we observe Greenwood-s model [1-2]. The Greenwood-s model is based on Hertz-s contact theory and represents simple and often applied method of describing rough surfaces. The question that arises is how big the actual-real contact surface is, by which contact is made, from that directly follows the magnitude of a contact force inside the contact interaction. Based on Hertz theory and Greenwood model we can set the basic equations of normal contact, that is, a total number of points that come in contact N, the surface of contact A and normal contact force F_N, [2]. On the other hand, if we observe contact of two or more bodies as an interaction of deformable continuum bodies for finite deformations we could say that analysis of contact of two or more bodies belongs to especially demanding nonlinear problems [3-5]. The nonlinearity of the analysis problem from now does not depend only on material and geometrical nonlinearity, which is usually studied in deformed bodies, but from contact conditions that are now included in the equation. Considering the contact problem, the equation of equilibrium for the N bodies in the contact on the right-hand side next to the expression of the external virtual work also contains the virtual work of the contact interaction (1). If L bodies are involved in the contacts $L=1,\ldots,N;$ where ${}^{t}S_{c}$ represents the total contact surface of each body, then the principle of virtual work for N number of bodies at time t is defined by the following expression, [3,5]:

$$\sum_{L=1}^{N}\left\{\int_{{}^{t}V}^{a} {}^{t}\tau_{ij}\ \delta_{t}e_{ij}^{T}\ d^{t}V\right\}=\sum_{L=1}^{N}\left\{\int_{{}^{t}V}^{a} {}^{t}f_{i}^{B}\delta u_{i}\ d^{t}V+\int_{{}^{t}S_{f}}^{a} {}^{t}f_{i}^{S}\delta u_{i}^{S}\ d^{t}S\right\}+\sum_{L=1}^{N}\int_{{}^{t}S_{c}}^{a} {}^{t}f_{i}^{c}\delta u_{i}^{c}\ d^{t}S \qquad (1)$$

Where part of a braces corresponds to the usual terms, while the last summation sign gives the force influence in a contact. As we can see contact force is represented as an exterior force. Components of equation of equilibrium are:

- ${}^{t}S_{c}$: complete contact area for each body L, L=1,..., N at the time t
- ${}^{t}f_{i}^{c}$: component of the contact traction act over the areas ${}^{t}S_{c}$
- ${}^{t}f_{i}^{S}$: components of the known externally applied tractions act over the surface
- ${}^{t}S_{f}$: surface at time t on which external tractions are applied
- δu_{i}^{c} : components of the virtual displacement on the contact surface
- ${}^{t}\tau_{ij}$: Cauchy stress tensor
- $\delta_{t}e_{ij}$: strain tensor corresponding to virtual displacements
- δu_{i} : components of virtual displacement vector imposed at time t
- ${}^{t}V$: volume at time t
- ${}^{t}f_{i}^{B}$: components of externally applied force per unit volume at time t
- $\delta u_{i}^{S}=\delta u_{i}$: components of virtual displacement vector

The objective of aforementioned text is to gain basic insights in the complexity of studying contact mechanics and cause of structural damping formation. For a detailed treatment of this subject the reader should consult the literature, e.g. [1-5]

3. EXPERIMENTAL AND MODEL DESCRIPTION

This experiment is performed on the bolted splice connection joint of the IPE-80 steel cantilever beam with modulus of elasticity of E = 210 GPa, and Poisson's ratio of v = 0.3, Fig. 2. IPE cantilever beam with bolted connection was rigidly bonded to the concrete wall via rigid angles and steel plate of thickness d = 20 mm and d = 30 mm. The IPE cantilever beam was welded to a 20 x 200 x 200 mm connection steel plate and additionally stiffened with rigid angles. All of it is then welded together for a carrying steel plate of 550 x 350 x 30 mm. The aforementioned dimensions of the carrying steel plate have been determined so that adequate connection and support of the complete system to a 300 mm thick concrete wall could be ensured. The complete system is connected to the concrete support with four M 20 bolts as shown in Fig. 2. The above-described method has achieved almost ideal clamped restraint which was primarily considered by a detailed numerical model.

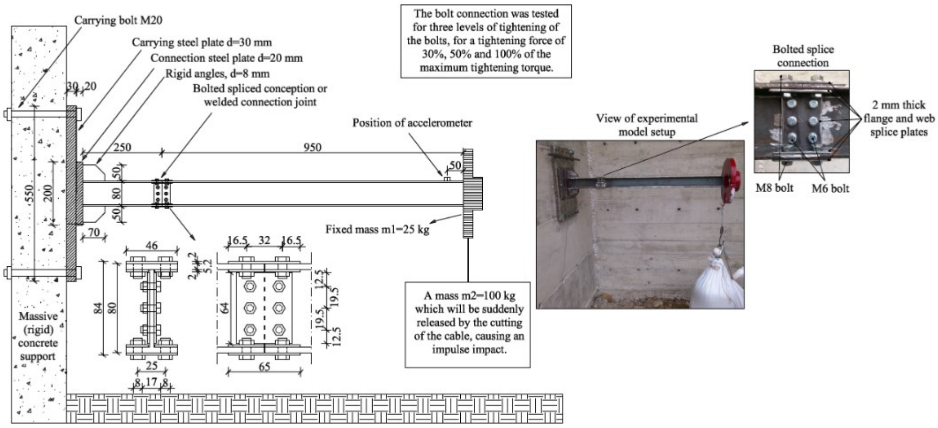

Figure 2. Layout of tested cantilever beam with joint detail

The splice connection is positioned near the support of the clamped beam, 250 mm from the support in order to receive as much momentum as possible. The splice connection joint should be loaded at 70 % of full capacity. In this way micro and macro slipping inside of connection contact interaction are accomplished with as little disturbing force as possible. A direct consequence of micro and macro slipping is the occurrence of structural damping due to friction in the connection joints. The bolted connection consists of the upper flange splice plate 65 x 45 x 2 mm in size and the two of lower small flanges splice plate 65 x 18 x 2 mm each, the web splice plates are 65 x 50 x 2 mm.

Table 1. Value of tightening torque and tightening bolt force

	Percentages of maximum tightening torque		Tightening torque M_u [Nm]	Tightening bolt force F_p [kN]
	30 %	±4 %	7	5
	50 %		11.5	8
	100 %		23	16

The connection was made with four M8 screws for the upper and lower flanges and six M6 screws for connecting the web. The bolted connection was tested for three different tightening forces in the bolts: 30%, 50% and 100% of the maximum allowable tightening torque for M8 and M6, 8.8 bolt quality, Table 1. The tightening torque of the screws is controlled by a torque wrench with a range of 4 to 40 Nm. A mass of 25 kg is fixed at the end of the cantilever beam to reduce the natural frequencies of the beam. Cantilever beam was excited with impulse load, accomplished with an instant released a mass of 100 kg with the cutting of the cable on which mass was hanged.

4. MODAL TESTING

For the experiment of utmost important is third mod (vertical). In the frequency response there is no major difference between a cantilever beam with a bolted connections. The reason for approximately the same modal frequencies for the three connection joints with different stiffness is the low mass of the modal hammer and therefore the small disturbing force by which the beam is excited. Due to the lack of sufficiently strong disturbing force slippage within the connection contact interaction could not occur, and the influence of frictional structural damping could not be activated. A slight oscillation of the modal frequency can be seen in the bolted connection with the tightening force of 30% - B30 of the maximum tightening torque. The occurrence of deviation is directly related to the micro slipping within the contact interaction of bolts, flange and flange splice plates, [6]

5. NUMERICAL MODELING AND VERIFICATION OF THE EXPERIMENTAL MODEL

A numerical FEM model is made using the Abaqus. The aim was to build numerical models to represent experimental models as accurately as possible. The model of the beam with bolted joints was developed with a 1 mm gap between bolts and the holes. Also 2 mm gap is provided between two solid parts of the IPE-80 profile, as in the experiment setup. Friction coefficient of 0.35 was adopted for all contact interactions, Abaqus [7].

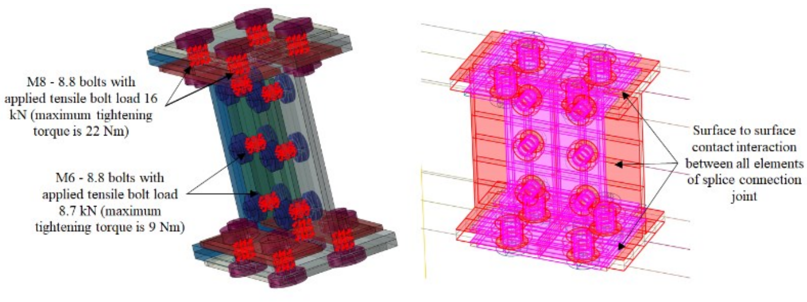

Figure 3. Detail of application of bolt load in Abaqus - left, dental of interactions

The clamping force of 16 kN was applied at the horizontal middle surface of the bolt to the M8 bolts and 8.7 kN for M6, Fig. 3. Choice of the element type has a great impact on analysis. After detailed analysis, numerical model built with 78 870 elements was adopted. When modeling, it is important to model a credible and accurate model with an optimal number of finite elements. It is easy to check that with poor mesh and an insufficient number of elements the required oscillation frequency can vary by up to 10%. Meshes with excessively high densities lead to costly calculations and in some cases increased numerical rigidity.

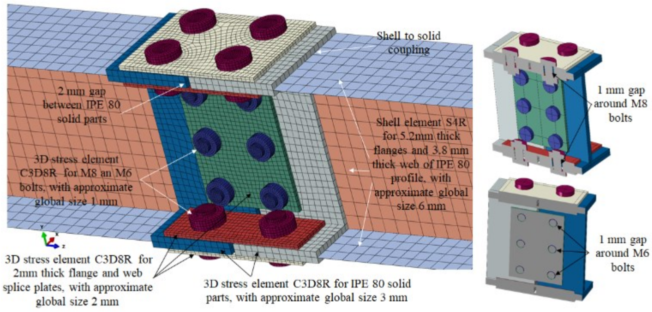

Figure 4. Bolted splice connection geometry with element type and mesh

The support structure and stiffening elements (concrete wall, M20 carrying bolts, 3 mm thick carrying steel plate, 2 mm thick connection steel plate and rigid angles) were modeled with three - dimensional hexahedral (C3D8R) elements. IPE-80 cantilever beam profile is modeled with two-dimensional (S4R) elements [7], while bolted and welded connection detail, Fig. 6 were modeled separately with three dimensional hexahedral (C3D8R) elements and jointed with two pieces of IPE-80 profile (S4R) using options Shell to solid coupling of elements. These elements were chosen since they can provide reasonable accuracy for the stress state during non-linear behavior at contact surfaces. The mesh was defined after thorough convergence check and dimensions of elements are shown in Fig. 4. In setting up the model the contact surfaces are built with finite elements of different size, in a way that slave surface (loaded surface) has a denser FEM mesh than master surface (loading surface) region, Fig. 3, 4. In this way, penetration between contact surfaces and initial overclosure were prevented. Also, better convergence rates were accomplished. Initial displacement was induced with load at the free end of cantilever, in the same way as in experimental setup. Load diagram is given in Figure 5, where Phase I represents loading and unloading process, while Phase II represents free vibration.

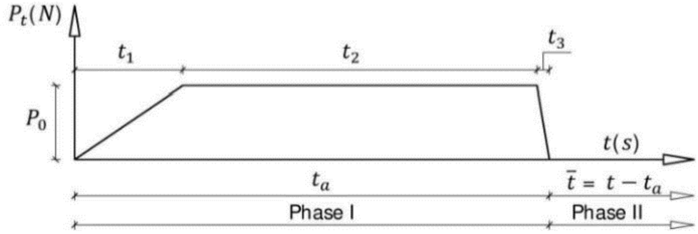

Figure 5. Load diagram

During modeling, significant influence of load release time t_3 was noticed. In order to calibrate numerical model, detail analysis of dependence of first four acceleration amplitudes versus release time is made. According to these results, t_3=15 ms is adopted.

6. NUMERICAL VERIFICATION OF THE EXPERIMENTAL MODEL

As we have previously concluded, accurate experimental testing of the mechanical characteristics of the connection joints requires sufficiently precise support conditions for the experimental model in this case of the cantilever beam. If there were some flexibility of support, even the small vibrations and displacements, the overall response of the structure would not be correct. Consequently, it would be impossible to separately study the influence of the bolted splice connection on the dynamic response of the cantilever beam. Numerical verification and analysis need to provide appropriate design recommendations of the elements and stiffeners to ensure that the constructed support is as close as possible to the mathematical model. By comparing the modal frequency of an ideally clamped numerical model with a numerical model designed to provide sufficiently rigid support for a cantilever beam, we will determine whether the links and stiffener are sufficient to provide clamped support, [6]. Further experimental verification and comparison of the experimentally obtained results with the numerical results showed that the construction of the experimental model has a satisfactory support stiffness, i.e. that an ideal clamped restraint is obtained. Numerical frequencies for the third and fourth mode are 15.78 and 68.51 Hz and experimental frequencies are 16 and 66.3 Hz. Comparison of the results of the numerical and experimental model, shows a small difference in the modal frequency, 1.68% for the third modal shape and 2.66% for the fourth modal shape.

7. RESULTS AND DISCUSSION

By analyzing experimentally obtained results of tested models it was obtained originally assumed a high difference of damping between bolt conection with tightening force of 100

% - (B100), 50 % - (B50) and 30 % - (B30). Experimental results of bolted connections give structural damping in the range of 0.007 to 0.06 depending on tightening torque of bolts. Accelerations in time domain along X direction are obtained for the and of the cantilever beam, where the accelerometer is positioned see Fig. 2. The envelope is obtained following equations of a system with single DOF. The equation of motion of free damped vibrations of this system, for damping less than the critical, is as follows:

$$y = Ae^{-\xi\omega t}\sin(\omega_d t) \quad (2)$$

where ω_d is free vibration frequency of the damped system and phase angle is $\phi = 0$. Acceleration is obtained after derivation of this equation with respect to time. Envelops are obtained for $\left[\sin(\omega_d t) = \pm 1\right]$

$$\ddot{y} = -Ae^{-\xi\omega t}\omega_d^2,\ \ddot{y} = Ae^{-\xi\omega t}\omega_d^2 \quad (3)$$

Unknown values are initial amplitude and damping ratio. By varying these values and harmonization of the envelope with acceleration graph, calibrated estimated values of initial amplitude and damping factor are obtained Fig.6. Based on compared diagrams for bolted models B30, B50 and B100 there can clearly be seen the difference in structural damping. It is noticeable that the amplitudes of oscillation fit in the envelopes of linear system of single DOF only in the beginning time, that is, already after a few oscillations amplitudes of oscillation cross the envelopes and are continuing to oscillate long after a total equalization of envelopes with X-axis. Faster deviation of amplitudes for model B30 with 30% tightening force than for model B100 with 100% tightening force indicates to greater dissipation at B30 model than at B100. Initial amplitudes of oscillation which occur after impact of impulse force are amplitudes of oscillation which originates while there was still enough energy in the beam after inducing impulse so the friction force in connections was exceeded and slipping in bolted connections has occurred which cause higher structural damping.

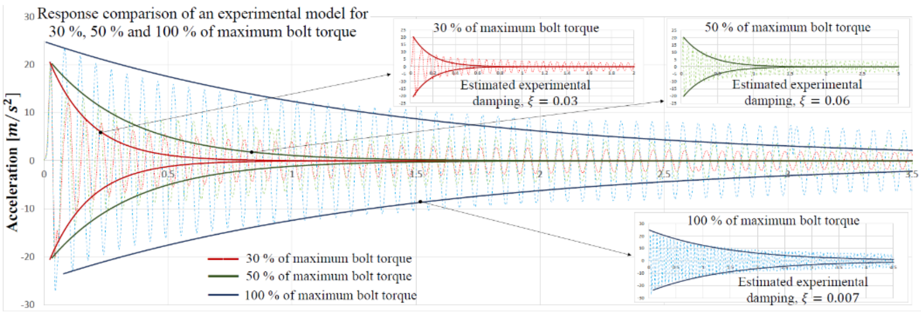

Figure 6. Model response with envelopes for Bolted connection joint for 30 % - B30, 50 % - B50 and 100 % - B100 of the maximum bolts tightening torque

While wasting energy the level of oscillations inside the beam and movement of contact surfaces inside bolted connection (flanges, bolts, and splice plates) is lowering so thereby also reducing damping. Micro slippings and constant process of contact asperities plastification as well as changing of contact surfaces geometry while interacting are always present in isolated regions between bolts. We could adopt totally fixed state - Stick state, to exist only between contact surfaces in small diameter around the body of high strength bolts.
Comparison of experimental and numerical results for models B100 and B30 are given in Fig. 7 and 8. The Abaqus model was calibrated only for the first several amplitudes, and afterward, disagreements with experiment are evident. Calibration of the first two amplitude highly depends on impulse force - the time of load release. As mentioned in section (5) time release is adopted as 15 ms. Although responses are not as those of one DOF system, damping is estimated using the logarithmic decrement approach for the first part of oscillation. Initial tests in Abaqus show that a perfectly symmetric model has negligible horizontal acceleration, but when small asymmetry is introduced at supports, this value significantly increases. Comparing the numerical model with the experimental model B100 and B30, we see that there is a much larger difference in the B30 model than in the B100 model. The reason for the increased deviation of the experimental model B30 from the numerical model is the much larger nonlinear effects in the bolted connection with 30% of the tightening force of the B30. In this case, the slippage is higher and the effect of the contact interaction on the damping is more significant than in the case of a connection with the full tightening force - B100.

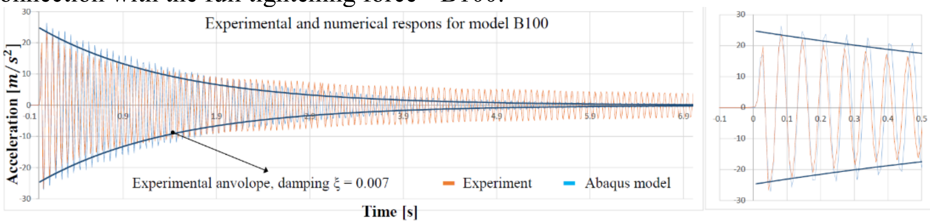

Figure 7. Experimental and numerical response for Bolted connection joint - B100

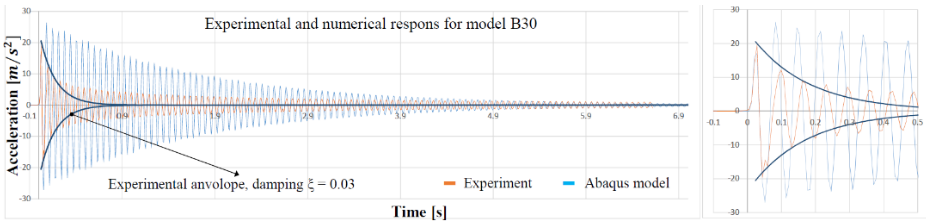

Figure 8. Experimental and numerical response for Bolted connection joint - B30

As the presented numerical model is analyzed using Modal Dynamics that is suitable for describing linear systems, where it is not possible to describe nonlinear phenomena and discontinuities within the contact interaction itself. When analyzing using Modal Dynamics, all elements remain in their places and slipping and moving of the connection elements in relation to each other is not allowed, therefore nonlinear effects are not included in the numerical response of the structure. For a better approximation of the experimental results, it is necessary to use an explicit analysis that allows the inclusion in the calculation of nonlinear effects within the contact interaction of the connection elements. It should be noted that due to the complex nature of friction and contact, it is not possible to fully simulate the nonlinear effects of contact interaction using an explicit method because the numerical code implemented in Abaqus software relies directly on Coulomb's law and cannot take into account geometry and real area of contact. To more accurately describe damping and energy dissipation in bolted connections, the greatest application and progress to date has been made by applying Iwan's Model for Mechanical Connections, [8].

8. CONCLUSION

This paper presented experimental and numerical investigations performed on a beam element. The goal was to investigate the effects of joints on the dynamic response of a structure, especially the damping characteristics. For this purpose a different cantilever beam models with bolted joints were experimentally tested. It's evident that the dumping is highly impacted by the bolts tightening force and friction. The main reason for the increase in damping is the contact frictional process between contact surfaces which are non-conservative and highly nonlinear. From this experiment, we can see the necessity of a better understanding of contact mechanics to enhance better understanding and define structural damping.

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НУМЕРИЧКА И ЕКСПЕРИМЕНТАЛНА АНАЛИЗА КОНСТРУКТИВНОГ ПРИГУШЕЊА ВИЈЧАНЕ ВЕЗЕ

Резиме: *Овај рад представља нумеричко моделовање вијчаних веза примјеном коначних елемната у динамичкој анализи како би се постигла разумна точност резултата симулације. Нелинеарни ефекти у монтажним наставцима укључују нормални притисак који држи дијелове везе заједно у комбинацији са динамичким бочним оптерећењима која узрокују смичуће проклизавање у контактној интеракцији елемената везе. Сама комплексност процеса проклизавања контактне интеракције одговорна је за нелинеарности које се јављају, како у погледу крутости тако и у дисипацији. Непосредно истраживање физике механичких веза није могуће из разлога нарушавања контактне интеракције између површина у контакту примјеном инструмената и мјерне опреме. Посљедице специфичних услова механичких веза јесу усложњавање динамичких проблема везаних са вибрацијама и дисипативним процесима у везама. Механичке везе су главни разлог за дисипацију енергије и појаву конструктивног пригушења. Циљ овог рада јесте представити одређене проблеме у вези с истраживањем конструктивног пригушења, те неопходност проучавања контактне механике ради дубљег и бољег разумијевања проблематике конструктивног пригушења.*

Кључне речи*: конструктивно пригушење, динамичке карактеристике, монтажне везе, контактна механика*