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EXPERIMENTAL ANALYSIS OF STRUCTURAL DAMPING FOR BOLTED AND WELDED SPLICE CONNECTION JOINT FOR IPE-80 STEEL PROFILE

Abstract:

Progress and demands of all types of constructions imposed the need for the development of modern structures that are lightweight, but at the same time have high damping capacity and stiffness. The consequences of these requirements are increased dynamic problems related to vibrations and dissipative processes in structure connection joints. Structural joints are the main reason for the significant reduction of the level of energy dissipation and source of structural damping so therefore they have become a subject of interest to many researchers. 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.

Keywords: Structural damping, dynamic properties, beam splice connections, Contact Mechanics

ЕКСПЕРИМЕНТАЛНА АНАЛИЗА КОНСТРУКТИВНОГ ПРИГУШЕЊА ВИЈЧАНЕ И ЗАВАРЕНЕ ВЕЗЕ МОНТАЖНОГ НАСТАВКА ЧЕЛИЧНОГ НОСАЧА IPE-80

Сажетак:

Напредак и захтјеви различитих врста конструкција наметали су потребу за развојем модерних конструктивних рјешења мале масе, али истовремено одговарајуће крутости и високе способности пригушивања. Посљедице ових захтјева су повећани динамички проблеми везани уз вибрације и процесе дисипације енергије у спојевима конструкција. Везе и спојеви код челичних конструкција главни су разлог значајног повећања нивоа дисипације енергије и настајања конструктивног пригушивања, па су постали предмет интереса многих истраживача. Циљ овог рада јесте представити одређене проблеме у вези с истраживањем конструктивног пригушивања, те неопходност проучавања контактне механике ради дубљег и бољег разумијевања проблематике конструктивног пригушења.

Кључне ријечи: Конструктивно пригушење, динамичке карактеристике, монтажне везе, контактна механика

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.

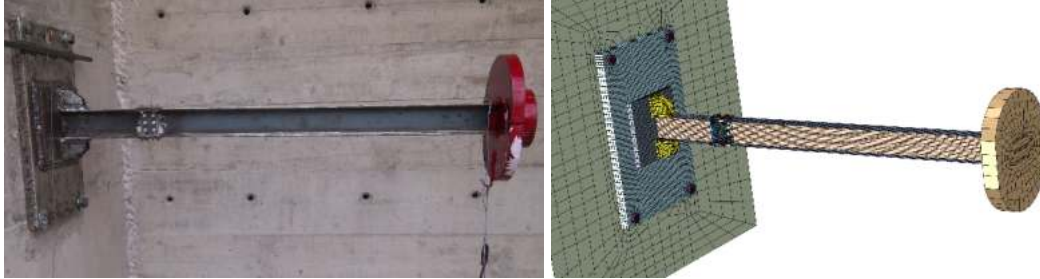


Figure 1. Model of experimental and numerical cantilever beam with bolted splice connection joint

On the other hand, the prediction of dissipative properties of a structure can be evaluated only experimentally, with a very careful and precise experimental setup. The complex nature of energy dissipation process stems from the nonlinear contact interaction behavior. In papers [1 - 3] authors investigated the effects of bolted and welded joints of one single connection extracted and examined separately from the main structure. They concluded that addition of bolted joints decreases the structure natural frequency by adding additional mass to the structure, and that usage bolts significantly increases the damping ratio. It is evident that using software such as the Abaqus and the Ansys, must be utilized for 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 and defined. In addition to the above, we can consider Coulomb's law of friction to be exact only in certain cases.

Although many researchers have been engaged in the analysis of the structural dynamic behavior, there is still not fully explained the impact of joints on the dynamic properties of the complex structure. This paper deals with numerical verification of experimental investigation of characteristics of bolted and welded splice connection joint.

2. THEORY

As we seen in Chapter 1 of this paper, structural damping is a direct consequence of friction in joints and splice connection of steel constructions. For one to obtain an exact value of structural damping it takes accurate description of two bodies in contact behavior, that is, it is necessary accurately to define interaction of contact surfaces, which is still not sufficiently researched and done. The relationship and complexity of structural damping and contact surfaces interaction can better be comprehended if we observe Greenwood-s model [4-5]. The Greenwood-s model is based on Hertz-s contact theory and represents simple and often applied method of describing rough surfaces Fig. 2.

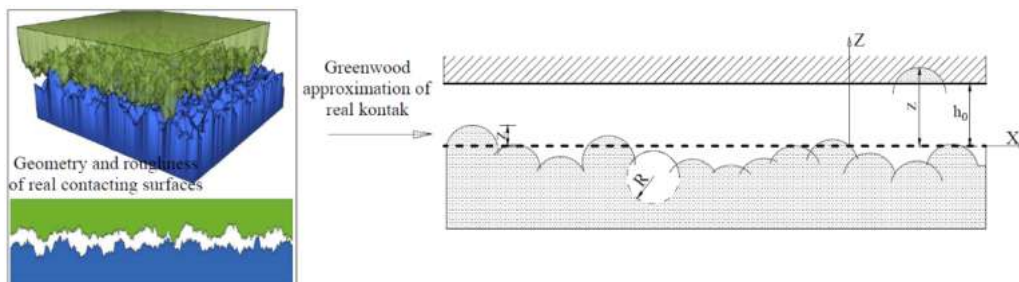


Figure 2. Greenwood approximation of real contact

Question that arises is how big the actual-real contact surface is, by which a contact is made, because 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, total number of points that come in contact N , surface of contact A and normal contact force F_N , [4].

$$N = \int_{h_0}^{\infty} N_0 \Phi(z) dz \quad (1)$$

$$A = \int_{h_0}^{\infty} N_0 \Phi(z) \pi R (z - h_0) dz \quad (2)$$

$$F_N = \int_{h_0}^{\infty} N_0 \Phi(z) E^* R^{1/2} (z - h_0)^{3/2} dz \quad (3)$$

where:

- h_0 : distance from the middle level of rough surface
- Z : asperity height
- R : radius of single contact asperity, as per Hertz contact theory
- N_0 : total number of asperities
- $\Phi(z)$: probability density of asperities height

Besides normal contact force, introducing in calculation the influence of tangential contact force the analysis of contact problem becomes significantly more complicated. Structural damping represents the resistance of mechanical connections joints while moving, that is, the size of the contact force of contact interaction prior to contact surface slip - Stick state, and after contact surface slip - Slip state. The complex process of elastic and plastic deformations of contact micro asperity, different magnitude of contact pressure and change in the size of actual contact surface, that is, constant change of contact geometry still represent challenge and requires further research so to better understand effects of structural damping.

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 [4-7]. 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 which are now included in the equation. Equation of balance in terms of current configuration expressed through Cauchy-s stress tensor is defined as

$$\int_{tV} {}^t\tau_{ij} \delta_t e_{ij} d^tV = \int_{tV} {}^tF_i^B \delta u_i d^tV + \int_{tS_f} {}^tF_i^S \delta u_i^S d^tS \quad (4)$$

where:

- ${}^t\tau_{ij}$: Cauchy stress tensor
- $\delta_t e_{ij}$: strain tensor corresponding to virtual displacements
- δu_i : components of virtual displacement vector imposed on configuration at time t
- tV : volume at time t
- ${}^tF_i^B$: components of externally applied force per unit volume at time t
- ${}^tF_i^S$: components of externally applied surface tractions per unit surface area at time t
- tS_f : surface at time t on which external tractions are applied
- $\delta u_i^S = \delta u_i$: components of virtual displacement vector

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 (5). If L bodies are involved in the contacts $L = 1, \dots, N$; where tS_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, [7]:

$$\sum_{L=1}^N \left\{ \int_V {}^t\tau_{ij} \delta_i e_{ij}^T d^tV \right\} = \sum_{L=1}^N \left\{ \int_V {}^t f_i^B \delta u_i d^tV + \int_{{}^tS_c} {}^t f_i^S \delta u_i^S d^tS \right\} + \sum_{L=1}^N \int_{{}^tS_c} {}^t f_i^c \delta u_i^c d^tS \quad (5)$$

Where part of a braces corresponds to the usual terms (4), 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 this force are:

- tS_c : complete contact area for each body $L, L=1, \dots, N$ at the time t
- ${}^t f_i^c$: component of the contact traction act over the areas tS_c
- ${}^t f_i^S$: components of the known externally applied tractions act over the surface tS_f
- δu_i^c : components of the virtual displacement on the contact surface

By further developing of contact virtual work in the expression (5) and by application of Hertz-Signoriny-Morau condition, expression (5) transforms from usual formulation where solution which needs to satisfy equilibrium equation goes into inequality of equilibrium which further complicates defining of contact interaction of two bodies and thus the problem of structural damping still remains unsolved [1], [2], [4]. 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. [4-8]

3. EXPERIMENTAL AND MODEL DESCRIPTION

This experiment is performed on the bolted and welded splice connection joints of the IPE-80 steel cantilever beam with modulus of elasticity of $E = 210$ GPa, and Poisson's ratio of $\nu = 0.3$, Fig. 3. IPE cantilever beam with the welded and 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 $20 \times 200 \times 200$ mm connection steel plate and additionally stiffened with rigid angles. All of it is then welded together for a carrying steel plate of $550 \times 350 \times 30$ 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 M20 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.

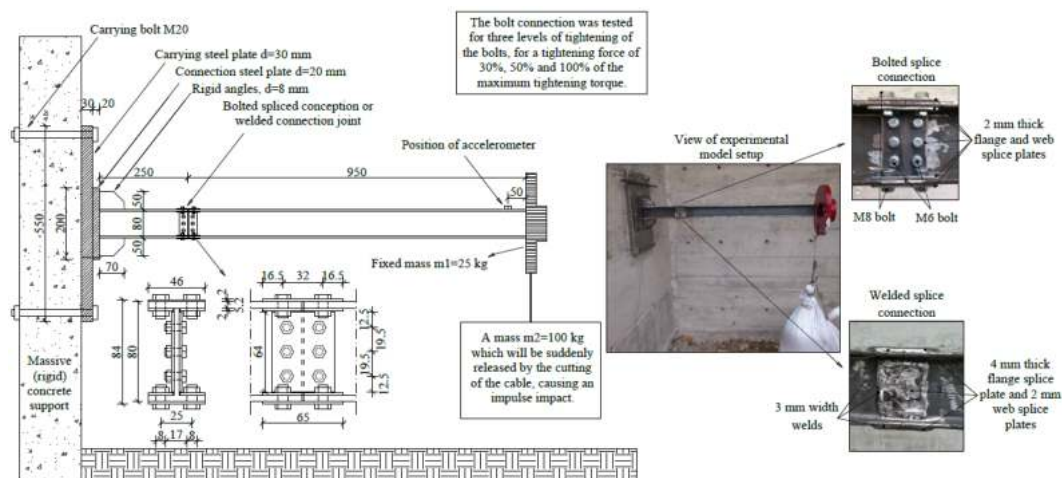



Figure 3. Layout of tested cantilever beam with joints detail

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. 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.

Table 1. Value of tightening torque and tightening bolt force

	Percentages of maximum tightening torque	$\pm 4\%$	Tightening torque M_u [Nm]	Tightening bolt force F_p [kN]
	30 %		7.5	5.5
50 %	11.5	8		
100 %	23	16		

The welded splice connection of the structural extension consists of one upper flange splice plate 65 x 45 x 4 mm and two web splice plates 64 x 50 x 2 mm. A mass of 25 kg is fixed at the end of the cantilever beam to reduce the natural frequencies of the beam. Each model of bolted and welded 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.

3.2. Modal testing

Modal testing was done on-site using the multi-channels acquisition system Portable Pulse 3560 C and the modal accelerometer type 4507, produced by Bruel&Kjaer. The modal hammer, type 2302-10 Endeveco, was used to excite the beam. The test was conducted for cantilever beam with bolted and welded splice connection joint, clamped at the end, Figure 3. The FFT analyzer was set up to frequency bandwidth of 0-200 Hz, with a frequency resolution of 0.25 Hz and with 3 linear averaging of root mean square values of acceleration amplitude. The recorded FRF responses function for modal testing of beams are shown in Fig. 4.

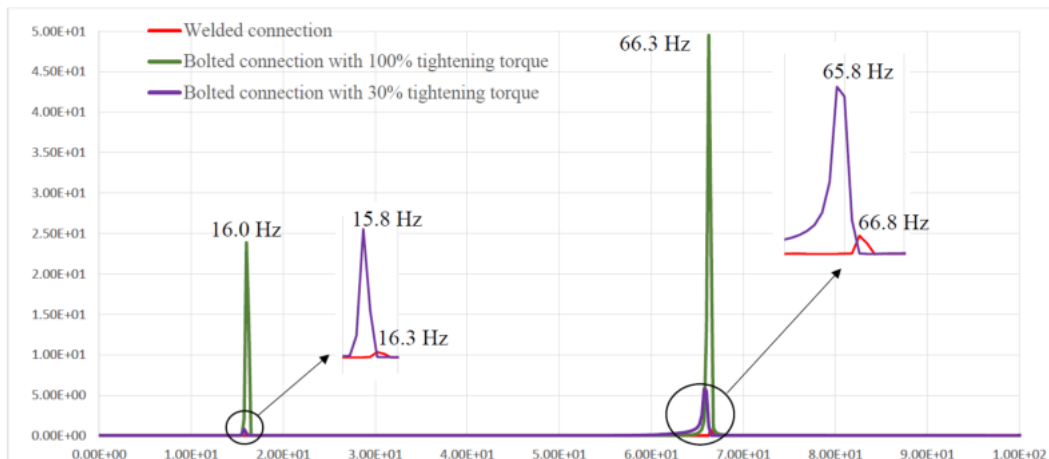


Figure 4. FRF functions measured in modal testing for different beam models

In Fig. 4, we can see the natural frequency values of the third and fourth oscillation modes of the cantilever beam with the bolted and welded splice connection. First two oscillation modes are not specified because of the specific setup and requirements of the experiment. An accelerometer was installed at the end of the cantilever beam in a vertical direction to provide as better as possible free vibration damped response. For the experiment of utmost important is third mod (vertical), the value of the first two modes are not clear. Because of everything mentioned above, these modes are not mentioned in the paper. The bolted connection is shown for two levels of tightening torque, 30%

and 100% of the maximum tightening torque for M8 class 8.8 bolts. As we can see in the frequency response shown there is no major difference between a cantilever beam with a bolted and a welded connection. 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% of the maximum tightening torque. The occurrence of deviation is directly related to the micro and macro slipping within the contact interaction of bolts, flange and flange splice plates.

4. NUMERICAL MODELING AND VERIFICATION OF THE EXPERIMENTAL MODEL

4.1. Principles of numerical modeling

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 0.70 was adopted for all contact interactions. The model of the beam with welded joints was developed without these gaps, similar to the experimental model connection. Welds are modeled like isolated interaction surfaces with Tie constraint option in Abaqus [9] with a width of 3 mm. With the explained procedure we have exactly defined thickness of the welds. 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. 5.

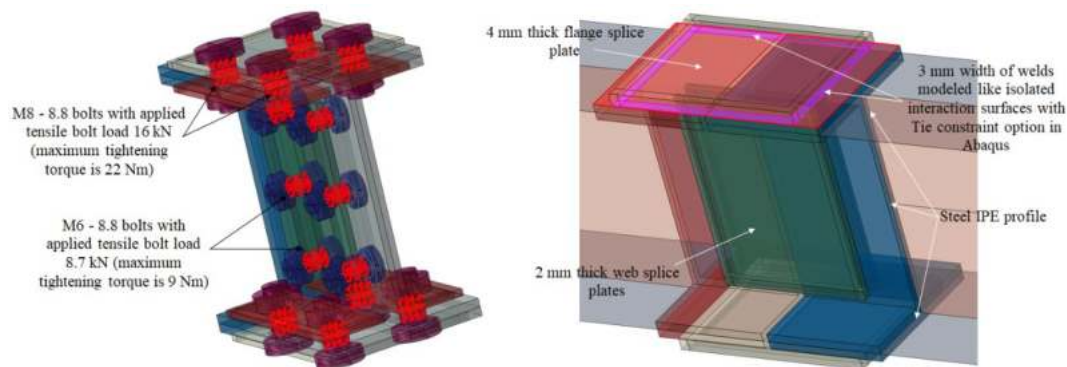


Figure 5. Detail of application of bolt load in Abaqus - left, detail of definition of weld thickness - right

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.

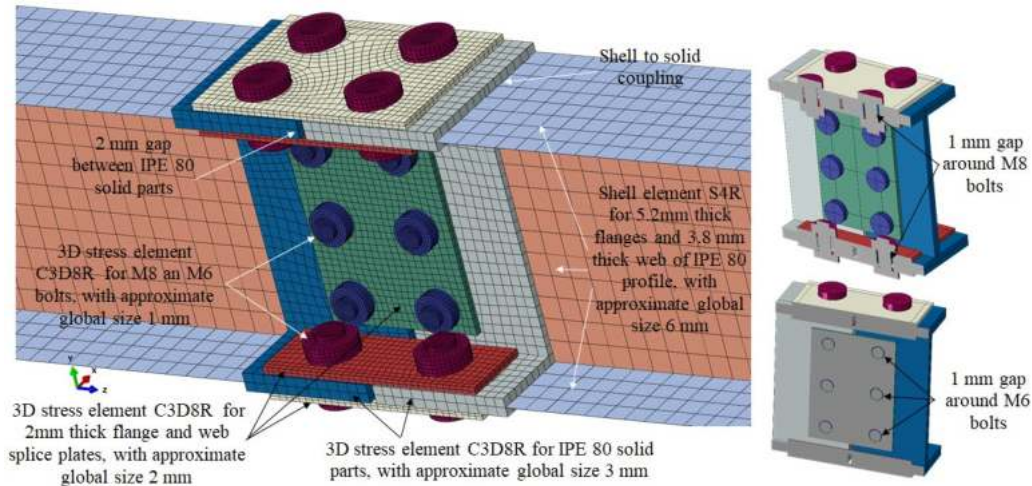


Figure 6. Bolted splice connection geometry with element type and mesh

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 [9], 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. 6. 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. 6. In this way, penetration between contact surfaces and initial overclosure were prevented. Also, better convergence rates were accomplished.

4.2. 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 and welded splice connection on the dynamic response of the cantilever beam.

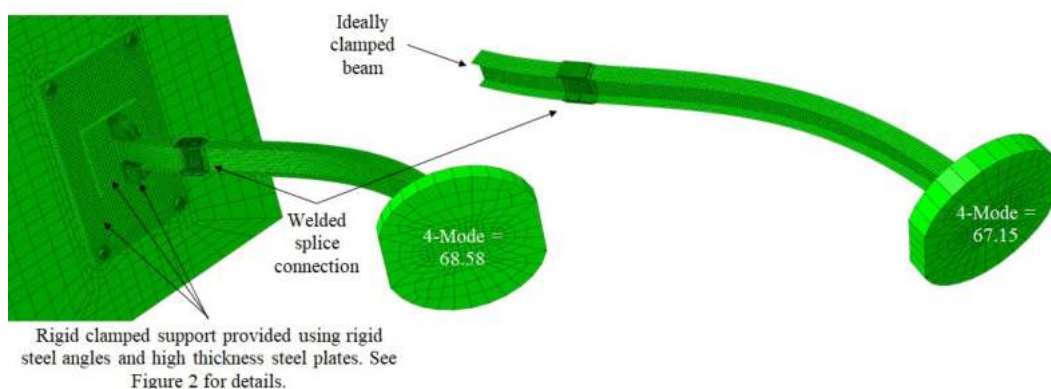


Figure 7. Fourth modal shape of rigidly clamped support for cantilever beam and ideally clamped cantilever beam

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.

Table 2. Modal frequency gained based on measurements and numerical results

Mark	Natural frequency (Hz) /mode shape type	Mode-1 (Lateral)	Mode-2 (Torsional)	Mode-3 (Vertical)	Mode-4 (Lateral)
[N1]	<u>Numerical</u> model - Ideally clamped beam (welded connection)	5.11 Hz	6.65 Hz	15.78 Hz	67.15 Hz
[N2]	<u>Numerical</u> model - rigid clamped support (welded connection)	5.28 Hz	6.74 Hz	16.03 Hz	68.58 Hz
[E1]	<u>Experimentally</u> tested cantilever (welded connection)			16.3 Hz	66.80 Hz
[N3]	<u>Numerical</u> model - rigid clamped support (bolted connection)	5.26 Hz	6.69 Hz	15.78 Hz	68.51 Hz
[E2]	<u>Experimentally</u> tested cantilever (bolted connection, 100 % tightening torque)			16.0 Hz	66.3 Hz

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, ie that an ideal clamped restraint is obtained, Fig. 7, Table 2. We can see by comparing models [N1] and [N2] from Table 2 that the first four modal frequencies of a numerical model with a designed support are higher than the frequencies of the ideally clamped model, which means that the dimensioned support stiffeners provide sufficient and slightly increased rigidity of the cantilever beam. The reasons for this difference are rigid angles, see Fig. 7 and Fig. 3, which increase the cross-section of the cantilever near the support in comparison with the ideally mathematically restrained cantilever. Further comparison of the results of the numerical model [N2] with the experimental model [E1], shows a small difference in the modal frequency, 1.68% for the third modal shape and 2.66% for the fourth modal shape.

As described earlier in Section 3.1, no significant difference was observed in the modal frequencies of the cantilever beam with the bolted and welded splice connection joint. Due to the low mass of the modal hammer and, consequently, the insufficiently large disturbing force, bolt connection was not excited and activated. The friction force respectively the tangential force within the bodies in contact was large enough to prevent the contact surfaces of the bolt connection from slipping. For the aforementioned reasons, no structural damping occurred, the cantilever with bolted splice connection joint acted as a monolithic beam, which behaves in the same way as the cantilever with the welded splice connection joint.

5. EXPERIMENTAL RESULTS AND DISCUSSION

By analyzing experimental results, it was confirmed the earlier assumption of high differences between bolted and welded joints damping. Welded connections give damping of 0.001 which is a range of material damping for steel that is, in boundaries below 0.01. Experimental results of bolted connections give structural damping in the range of 0.008 to 0.06 depending on tightening torque of bolts. The recommendation of Euro Code BS EN1998-1: 2004 section 3.2.2.2. and BS EN1998-6:2004 section 4.2.4 for standard steel constructions is damping of 0.05, while for different adopted damping further defining is needed. Depending on different authors damping vary from 0.03 to 0.10.

Accelerations in time domain along X direction are obtained for the end of the cantilever beam, where the accelerometer is positioned see Fig. 3. 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:

$$y = Ae^{-\xi\omega t} \sin(\omega_d t) \quad (6)$$

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:

$$\ddot{y} = Ae^{-\xi\omega t} \left[\xi^2 \omega^2 \sin(\omega_d t) - 2\xi\omega \cos(\omega_d t) \omega_d - \sin(\omega_d t) \omega_d^2 \right] \quad (7)$$

Terms $\xi^2 \omega^2 \sin(\omega_d t)$ and $2\xi\omega \cos(\omega_d t) \omega_d$ can be neglected, because they do not affect results significantly, and also damping estimation is much easier. After neglecting these two terms the equation remained is following:

$$\ddot{y} = Ae^{-\xi\omega t} \left[-\sin(\omega_d t) \omega_d^2 \right] \quad (8)$$

Envelops are obtained for $[\sin(\omega_d t) = \pm 1]$

$$\ddot{y} = -Ae^{-\xi\omega t} \omega_d^2, \dot{y} = Ae^{-\xi\omega t} \omega_d^2 \quad (9)$$

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.8, Fig.9 and Table 3.

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 nonlinearity at B30 model than at B100.

Table 3. Estimated value of damping for all models

Mark	Experimental model	Damping ξ	Differ. (%)
B30	Bolted connection with 30 % of tightening torque	0.06	Difference between model B30 and B50
			100
B50	Bolted connection with 50 % of tightening torque	0.03	Difference between model B30 and B100
			650
B100	Bolted connection with 100 % of tightening torque	0.008	Difference between model B50 and B100
			275
W	Welded connection	0.001	Difference between model B100 and W
			700

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.

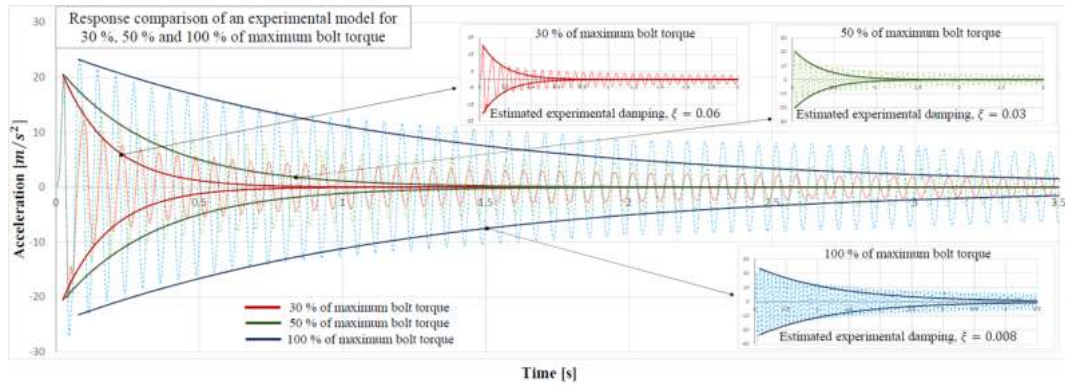


Figure 8. Model response with envelopes for Bolted connection joint for 30 % - B30, 50 % - B50 and 100 % - B100 of the maximum bolts tightening torque

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. Cantilever beam continues to oscillate as monolithic beam without bolted connection, which can be seen from long fade out of steady stated oscillations

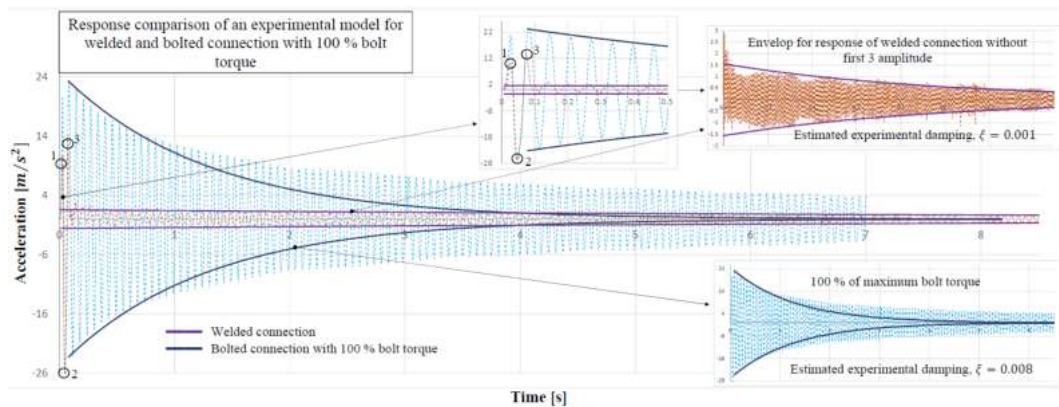


Figure 9. Model response with envelopes for Bolted connection joint with B100 - 100 % of the bolts tightening torque and welded conception

With further comparison of results of free damped oscillation of welded model W and bolted model B100, we see the difference in damping of 700% Table 3, Fig. 9. Interesting is to notice that there is greater difference in damping between model with 100% tightening torque B100 and welded model W, than between bolted models B100 and B30, considering that connection with tightening torque of only 30% is almost completely loose and untight.

This high difference of damping, points to significance of micro and macro slipping between surfaces of bolted connection elements. Because of usage 8.8 bolts in this experiment, macro and micro slip are occur and therefore high damping is evident.

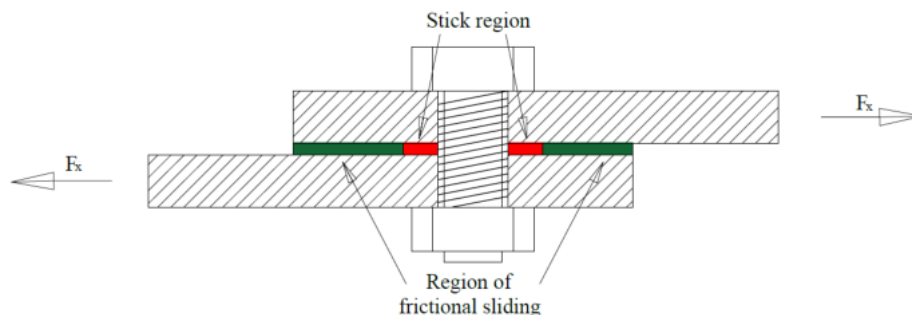


Figure 10. Contact regions in a lap joint

Regardless of bolt tightening level micro slippings are always present and therefore also the occurrence of energy dissipation, that is, structural damping. With high strength bolts macro slips

and movement of connection elements one in relation to the other are prevented by high tightening force of bolts Fig. 10.

Micro slips and constant process of contact asperities plastification, as well as changing of contact surfaces geometry while interacting is 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.

6. CONCLUSION

This paper presented a detail experimental investigation 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 welded and bolted joints were experimentally tested by means of modal testing and free decay testing. Fundamental natural frequency determined from FRF functions measured in modal testing is a little lower for a model with a bolted joint than for a model with a welded joint.

The reason for this almost insignificant difference between bolted and welded connections is because of the small weight of impact hammer and therefore the disturbing force is not large enough to excite the bolted connections joint to oscillate and activate slipping within the contact interaction of the bolted connection. Anyhow, investigated beam models were identical between each other, the influence of additional mass coming from bolts to frequency reduction was excluded. This small difference in natural frequency proves that structure with welded joint, i.e. the monolithic structure has higher stiffness compared to structure with bolted joints.

Similar results are obtained regarding damping characteristics that come from free decay test, where damping was estimated from logarithmic decrement. It's evident that the dumping for bolted connection is higher than for welded i.e. the monolithic model. The main reason for increase of damping is the contact frictional process between contact surfaces which are non-conservativ and highly nonlinear.

From this experiment, we can see the necessity of a better understanding of contact mechanics to enhance better understanding and define of structural damping.

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