RELIABILITY OF SEISMIC LINKS IN ECCENTRICALLY BRACED STEEL FRAMES

M. Čaušević [1], M. Bulić [2], B. Androić [3]

[1] *Professor, University of Rijeka, Faculty of Civil Engineering, Rijeka, Croatia*
[2] *Assistant, University of Rijeka, Faculty of Civil Engineering, Rijeka, Croatia*
[3] *Professor, University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia*
Email: mehmed.causevic@gradri.hr

ABSTRACT :

In this paper theoretical and experimental research of the most ductile elements of the eccentrically braced steel frames called seismic links is presented. Four types of **short seismic links** were chosen, each having the same cross section HEA100 and the same length, but with different number of stiffeners, i. e. with three couples of stiffeners, two, one and without any stiffener on the seismic link length.
First of all the nonlinear numerical modelling was conducted by the finite element method. Results of this theoretical analysis served as a base for preparing the scope for experimental analysis. Four series (realized in two sets) of experiments each having four specimen of short seismic links with different number of stiffeners were conducted.
The first set of experiments was made on the whole model of eccentrically braced steel frame. The second set of experiments was conducted with the auxiliary structure simulating boundary conditions for links in the real eccentrically braced steel frames.
To obtain the degree of reliability of eccentrically braced steel frame the reliability index β was defined on the probabilistic level in relation to target value for the reliability class RC2 according to Eurocode 0 [6]. It has been concluded that the optimum reliability index β is obtained for short seismic links with two and three pairs of web stiffeners for reliability class RC2 and 50 year reference return period.

KEYWORDS: seismic links, steel frames, reliability index, nonlinear analysis, seismic energy, eurocodes

1. INTRODUCTION

Eccentrically braced steel frames are hybrid systems that combine frame stiffness of centrically braced frames with ductility and capability to dissipate seismic energy of moment resisting frames [13] of which at least one end of the bracing is connected to the beam so as to form a segment in the beam called seismic link (Figure 1).

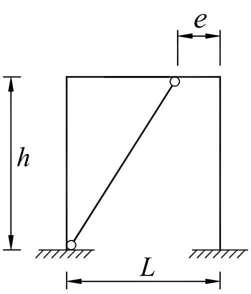

Figure 1. A simple eccentrically braced frame

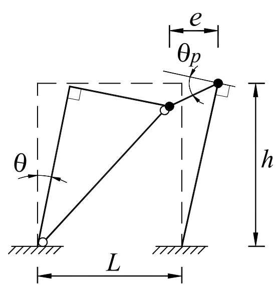

Figure 2. A collapse mechanism

It is well known that seismic links are usually designed to remain in elastic region during ordinary loading but withstand nonlinear deformation during seismic event, having capability to dissipate seismic energy. The critical factor which influences the inelastic behaviour of the link is its length which is correlated to the capability to dissipate seismic energy and the collapse mechanism (Figure 2) of the system [11]. In such a system the danger of brace buckling may be prevented since the seismic link acts as a fuse which limits the axial force in the bracing.

The seismic link should be designed so that it may bear great inelastic deformations without losing resistance and so that most of the seismic energy is dissipated within it [5].
Analytical and experimental analysis in this work was restricted to the analysis of short seismic links because they are capable of dissipating seismic energy in larger quantity by shear, while the webs in these links are expected to yield in shear during large seismic events [10]. To achieve the required plastic rotation, local instabilities such as flange or web buckling are delayed. The flange local buckling is delayed by specifying width to thickness ratio, while the web local buckling will be prevented by adding number of transverse stiffeners along the web of the link [12].

2. DESIGN OF SEISMIC LINKS

Seismic links are designed for the experiments which will be presented in this paper, using Eurocode 8 [8], for the computed seismic action effect in shear V_{Ed} or in bending M_{Ed} of the link, so that

$$V_{Ed} \leq V_{p,link} \qquad M_{Ed} \leq M_{p,link} \tag{2.1}$$

where $V_{p,link}$ and $M_{p,link}$ is, respectively, the plastic shear and bending resistance of the link which, for I sections, have the following values [8]:

$$V_{p,link} = \left(d - t_f\right) \cdot t_w \cdot \frac{f_y}{\sqrt{3}} \qquad M_{p,link} = b \cdot t_f \cdot \left(d - t_f\right) \cdot f_y \tag{2.2}$$

if $N_{Ed} / N_{pl,Rd}$ in the link is less or equal to 0,15.
The plastic mechanism in seismic links depends on their length, *e*. Short links yield essentially in shear; the energy dissipated in the plastic shear mechanism is
$W_V = V_{p,link} \cdot \theta_p \cdot e_s$.
Long links e_L yield essentially in bending. The energy dissipated in the plastic mechanism of long links that are subject to action of equal bending moments at the ends has value:
$W_M = 2M_{p,link} \cdot \theta_p$.
The limit between long and short links corresponds to a situation in which yielding may take place either in bending or in shear:

$$W_M = W_V \Rightarrow 2M_{p,link}\theta_p = V_{p,link} \cdot \theta_p \cdot e \Rightarrow e = 2M_{p,link} / V_{p,link} \tag{2.3}$$

However, for values of *e* around the limit of Eqn. (2.3), significant bending moments and shear forces exist simultaneously and their interaction has to be considered [8], [12].
Web stiffening of the seismic link improves the capability of dissipating seismic energy in the link by delaying the inelastic web buckling and it slows down the decrease of the load bearing capability of the seismic link by controlling the displacement amplitude outside the web plane. Dissipation of energy in the stiffened link will occur sooner through inelastic shear deformations than through inelastic web buckling [10].

3. ANALYSIS OF SPECIMENS

3.1. Choice of specimen dimensions for analysis

For the analysis the specimen of short links in which yielding will occur due to shear were chosen. Four specimen with an equal cross-section (HEA100) and equal length (e_s = 300*mm*) were chosen and the number of stiffeners, that is, the actual distance between stiffeners $a_{ac\ i}$ was varied (Figure 3):

a) Specimen of seismic link without stiffeners (a_{ac0} = 300*mm*)

b) Specimen of seismic link with one couple of stiffeners (a_{ac1} = 150*mm*)

c) Specimen of seismic link with two couples of stiffeners (a_{ac2} = 100*mm*)

d) Specimen of seismic link with three couples of stiffeners (a_{ac3} = 75*mm*)

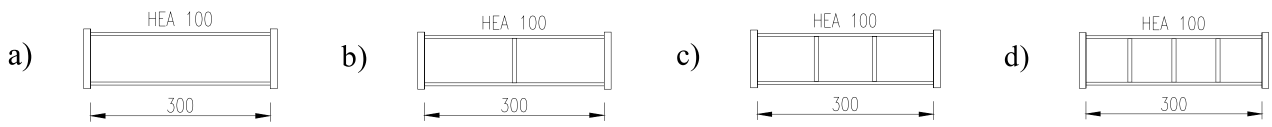

Figure 3. Specimen of short links

The link length for this analysis was chosen in a way to fulfill the requirements of Eurocode 8 [8] for both short links

$$e < e_s = 1{,}6\ M_{p,link} / V_{p,link}$$

and distance between link stiffeners

$$a_{com} = 30 t_w - d/5 \qquad (3.1)$$

Having this in mind the following value for short link length was used in this analysis: $e_s = 1{,}1\ M_{p,link} / V_{p,link} = 300mm$.

Nominal geometric characteristics of the cross-section were adopted (HEA 100) for all specimen. 15 mm thick endplates were placed at the ends of the seismic links. Web stiffeners are 10*mm* thick plates [8], placed bilaterally. Boundary conditions for links are defined in a way as to simulate boundary conditions in the frame. On one side of the link all six conditions of freedom were prevented, while on the other side (left, Figure 2) five conditions of freedom were prevented and displacement on the vertical axis was allowed.

3.2. Finite element modelling

The programme package STRAUS [16] was chosen for execution of numerical simulations using the method of finite elements. The applied Solid 3D (8-nodal brick) elements, although much more complicated to model than plane elements, give more accurate results and are recommended for scientific numerical simulations of steel systems. The nonlinearity of actual materials was introduced into the numerical model. Finite element analysis of the seismic link was done on base of actual mechanical characteristics of the material which are obtained experimentally, $f_{ya} = 321{,}74 N/mm^2$ [4].

At the connection of the endplate to the seismic links and at the connection of the stiffeners to the profile, it was necessary to find a network of finite elements that would correspond to the network of finite elements of the profile. A model without stiffeners is composed of 24072 elements, a model with one couple of stiffeners has 25496 elements, a model with two couples of stiffeners has 26920 elements and finally a model with three couples of stiffeners is made up of 28344 elements (Figure 4).
Fillet welds connecting a link stiffener to the link web should have a design strength adequate to resist a force of $\gamma_{ov} f_y A_{st}$, where A_{st} is the area of the stiffener and γ_{ov} is material overstrength factor . The design strength of fillet welds fastening the stiffener to the flanges should be adequate to resist a force of $\gamma_{ov} f_y A_{st} / 4$ [8].

$$f_{ya} = 321{,}74 N/mm^2,\ f_y = 235{,}00\ N/mm^2,\ \gamma_{ov} = f_{ya}/f_y = 321{,}74/235 = 1{,}37$$

$$F_{Rd} = \gamma_{ov} f_y A_{st} = 1{,}37 \cdot 235\ N/mm^2 \cdot 470\ mm^2 = 151.316\ N$$

The thickness of fillet welds was chosen $a = 5\ mm$. Design resistance of fillet welds is:

$$F_{w.Rd} = \frac{1}{\gamma_{Mw}} \frac{f_u}{\beta_w \sqrt{3}} \cdot a \cdot L = \frac{1}{1{,}25} \frac{360}{0{,}8\sqrt{3}} \cdot 5 \cdot (2 \cdot 80) = 166.277\ N$$

The 5 *mm* thickness of fillet welds fulfils all these requirements, i. e. the fillet welds strength is higher than strength of the basic material [7].
Models were loaded by adding vertical displacement in 1 *mm* increments on one end of the link, which simulated web plastification due to shear force action (Figure 4).
A comparison of numerical results for four models of short seismic links (described in 2.1) was conducted.

Change of stress in the web while adding displacements in 1*mm* increments on one end of the link is illustrated graphically (Figure 5).
It may be noted that models without stiffeners and models with one couple of stiffeners behave similarly. In models with two and three pairs of stiffeners a greater region of material yielding may be noted which means that the web plastification in this region occurs without the buckling of the web plate.

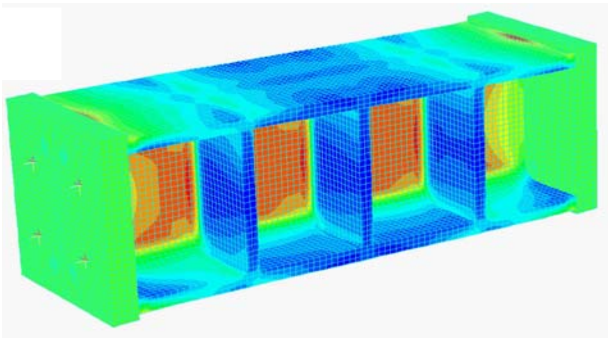

Figure 4. Finite element mesh after web plastification

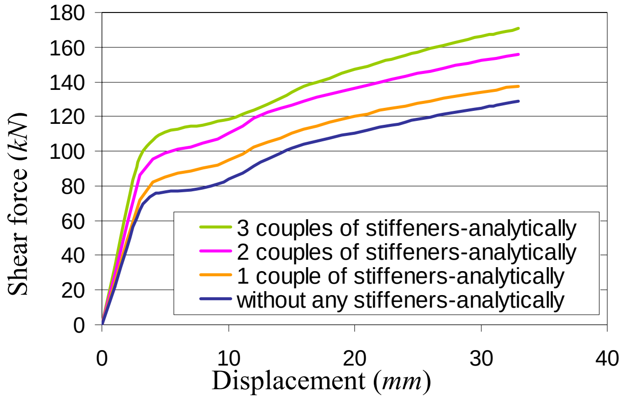

Figure 5. Analytically obtained Shear force-Displacement Relationships for short seismic links

3.3. Experimental analysis

The scope for experimental testing was established on the base of obtained analytical results. Experimental analyses were performed at the Laboratory for structures at the Faculty of Civil Engineering, University of Zagreb. This laboratory research was conducted on four series (realized in two sets) each having four specimen of short seismic links with different number of stiffeners. The first set of experiments was conducted on the realistic simple frame model in the scale of 1:3 (Figure 6) while the second set was conducted on an auxiliary structure where boundary conditions of seismic links were simulated (Figure 8).
Due to space limitation in laboratory, a simple frame with one eccentrically braced steel frame was chosen. The width and height of the frame are 2*m* each and the length of the seismic link is 0,3*m*. Having restriction in the laboratory for horizontal application of force, the model of an eccentrically braced frame is placed in a position rotated for 90° (Figure 6).
Loading is applied statically using an actuator type Zwik/Roell of capacity up to 2000 *kN* (Figure 6). Vertical and horizontal displacements are measured for each specimen using the LVDT device and the web strain of the seismic link is measured by the use of tensometrical gauges (Figure 7).

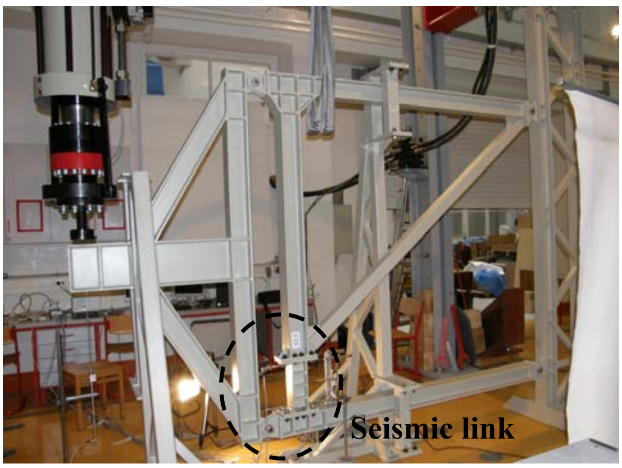

Figure 6. The model before testing

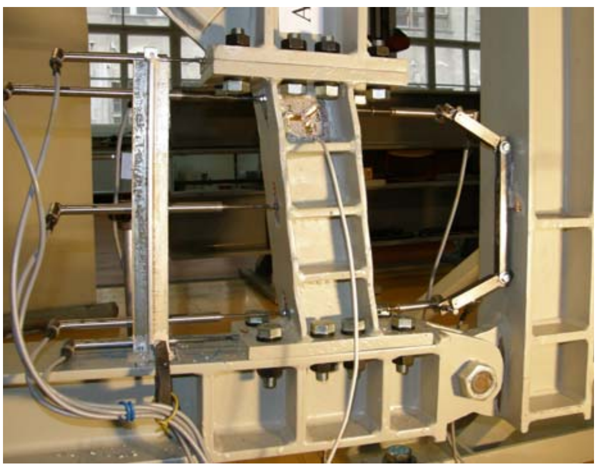

Figure 7. The seismic link of the same model after testing

The second set of experiments was conducted on an auxiliary structure so that the seismic links were examined in pairs (Figure 8). The aim of this experiment was to establish the behaviour of seismic links without influence of other frame elements.
The loading was applied up to the displacement of seismic link to 44 *mm* which corresponds to the rotation angle of 0,16 *rad* (Figure 9).

Figure 8. Testing on auxiliary structure

Figure 9. Specimen B2-2 of seismic link after testing

3.4. Comparison of the analytically and experimentally obtained results

On the base of experimental testing of the seismic links with different number of stiffeners Shear force-Displacement Relationships was obtained (Figure 10). Behaviour of different seismic links in elastic region is identical. When adding stiffeners, shear force at which the seismic link yields, increases. The seismic links without stiffeners yield at shear force 63 *kN*, while the seismic links with three couples of stiffeners yield at shear force 98 *kN*, which is an increase of 55%.
The comparison of results obtained by nonlinear numerical analysis by finite elements method (Figure 5) and experimental results for all four types of seismic links (Figure 10) is presented in Figure 11. It can be concluded that the theoretically and experimentally obtained results correspond very well for all four seismic link types.

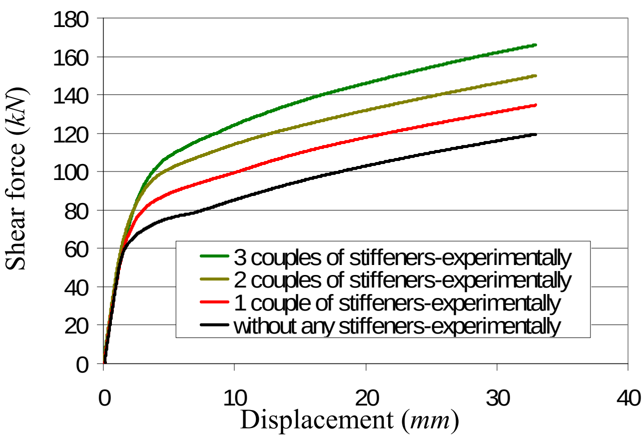

Figure 10. Experimentally obtained Shear force-Displacement Relationships

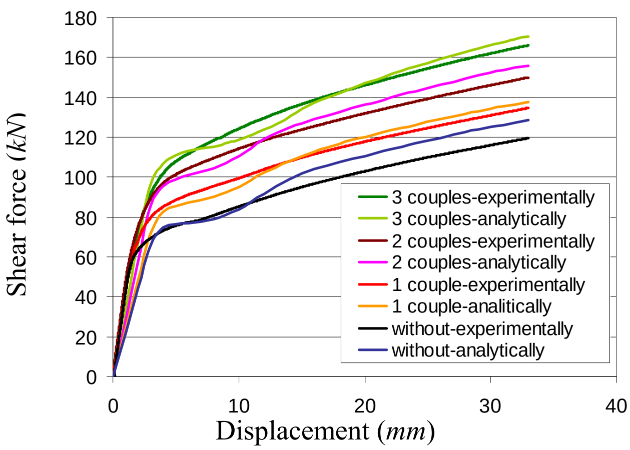

Figure 11. Comparison of results obtained experimentally and analytically

4. PROBABILISTIC ANALYSIS

4.1. General

To obtain the proper degree of reliability of the structure it is necessary to take into consideration the stochastic nature of both the structure properties and the actions on structure [2]. Namely, the actual values of the mechanical characteristics of the material and the geometric characteristics of the elements deviate from ideal values (imperfections). During design of the structure actions differ in reality from the supposed ones.
All parameters of unreliability in a probabilistic analysis are taken into consideration through stochastic variables which are called basic variables. They characterize behaviour and reliability of the structure and are defined by their mean value, standard deviation and probability density function.
Proof of reliability for different models of seismic links is conducted by forming both: the limit state equations and the stochastic model (description of the statistical nature of basic variables), and calculating the related reliability index β [3].
Eccentrically braced steel frames are estimated to be categorized in the reliability class RC2 [6]. Targeted value of the reliability index β in this case is 3,80 for a reference return period of 50 years, according to eurocode [6] and reference [14]. A limit state equation is formed for each model [3]:

$$g(\overline{X}) = R - E = V_{p,link} - V_E = 0 \tag{4.1}$$

where:
$g(\overline{X})$ – is the limit state function that connects all basic variables and constants
R – is the function of resistance with basic variables and constants on the part of resistance
E – is the function of the action effect with basic variables and constants on the part of action.

4.2. Basic variables and the limit state equations

In the probabilistic concept of reliability, the material properties, geometrical properties and action effect are defined as basic variables. Basic variables are defined as a one-dimensional stochastic model and are described with appropriate distribution functions, i.e. they are determined by type of distribution, mean value μ and standard deviation σ. Basic variables on the part of resistance: γ_i factors of model correction, f_{yw} yield strength of web of link, t_w web thickness, t_f flange thickness, $a_{ac\ i}$ actual spacing of web stiffeners. Basic variable on the part of action: V_E action effect (shear force) of earthquake [3].

4.3. Reliability index

Calculation of the reliability index β as an operative value of the probability of collapse was conducted through the use of a computer programme package VAP described in [14] which enables computation of the reliability index according to the *First Order Reliability Method* – FORM.

4.3.1. Results obtained from reference data

The preliminary probabilistic analysis using statistical parameters of base variables adopted from references [15] was conducted and reliability index values for four chosen short seismic link types were obtained.

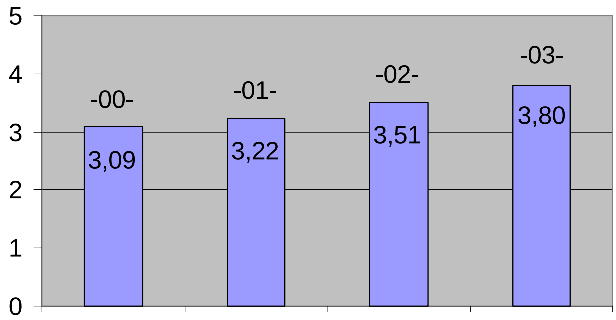

Figure 12. Reliability index β (FORM, theoretically)

Values of reliability index β according to FORM for the observed specimen of seismic links are $\beta = 3{,}09$ for specimen without stiffeners (-00-), $\beta = 3{,}22$ for specimen with one couple of stiffeners (-01-), $\beta = 3{,}51$ for specimen with two couples of stiffeners (-02-), and $\beta = 3{,}80$ for specimen with three couples of stiffeners (-03-), Figure 12, [3].
For seismic links with three pairs of stiffeners the reliability index of $\beta = 3{,}80$ was obtained which is the targeted value for reliability class RC2 and the reference return period of 50 years.

4.3.2. Results obtained from own experiments

The statistical parameters of basic variables were obtained from experiments in a way of dimension control, real yield strength of the web and flange of links and factors of model correction. The calculated reliability index values β according to FORM for analyzed seismic links are from $\beta = 3{,}28$ for seismic links without stiffeners to $\beta = 3{,}95$ for seismic links with three pairs of stiffeners, Figure 13. For the seismic links with two and three pairs of stiffeners the reliability index larger than 3,80 was obtained. Experiments proofed that the short seismic links with two and three pairs of web stiffeners have a higher reliability in comparison with reliability obtained following Eurocode 8 [8].
The significance of particular basic variable is expressed by sensitivity factors α_i which represent the reliability index sensitivity regarding their mean value and standard deviation.
Since the sensitivity factors present the ″weight″ of each basic variable regarding its influence on the value of the reliability index, results of analysis pointed out that the following basic variables have an increased influence on reliability index β (Figure 14) [3]: t_w – web thickness; V_E – action effect (shear force) of earthquake

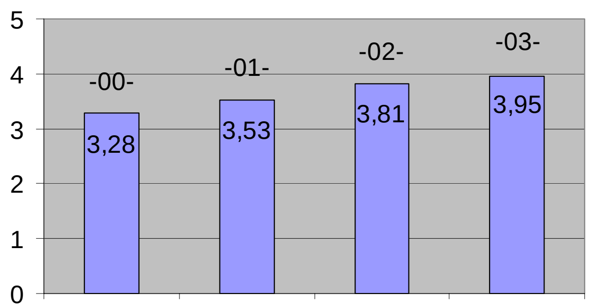

Figure 13. Reliability index β (FORM, experimentally)

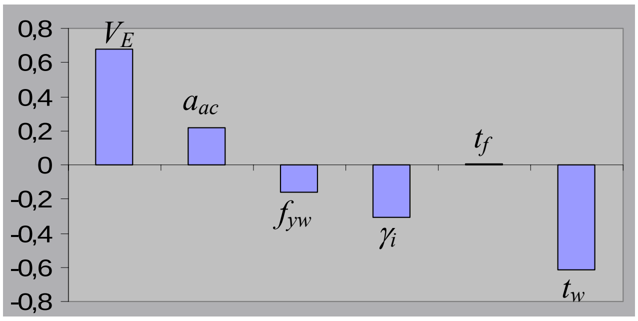

Figure 14. Sensitivity factors α_i (experimentally)

This result points out both the importance of dimension control of web thickness during future experimental research and the significance of an accurate estimation of seismic load variability.

5. CONCLUSIONS

The research of short seismic link reliability was conducted and presented in this paper for eccentrically braced steel frames following a resistance model for short link length and shear web stiffener distance according to Eurocode 8 [8].
Nonlinear numerical analysis was conducted preliminary using the finite elements method which served as a base for planning the experimental research. In order to analyze the approximate reliability index values and basic variables sensitivity factor, before the experimental research a preliminary probabilistic analysis was performed.
From the probability analysis results it is concluded that the values of reliability index β which were obtained from data of experimental analyses are larger than the values of reliability index obtained from the preliminary analysis using reference data. A reliability index of $\beta = 3{,}81$ was obtained for short seismic links with two pairs of stiffeners while a reliability index of $\beta = 3{,}95$ was obtained for short seismic links with three pairs of stiffeners which means that they are larger than targeted value $\beta = 3{,}80$ according to Eurocode 0 [6] for reliability class RC2 and reference return period of 50 years. Lower reliability indexes ($\beta < 3{,}80$) are obtained

for short seismic links without stiffeners and with one pair of stiffeners. According to the obtained base variable sensitivity factors it can be concluded that the web thickness t_w on resistance side and the seismic effect (shear force) V_E on the action side have a prevailing influence on reliability index.
The probabilistic analysis on theoretically and experimentally obtained results proofed that the short seismic links with two and three pairs of web stiffeners designed according to requirements of Eurocode 8 [8] have enough reliability which is greater then targeted value 3,8.

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