INTRODUCTION

Beam-to-column joints of steel frames traditionally have been modelled either as ideally pinned or ideally perfectly rigid. However, even though the model of structure with ideal joints simplifies the analysis procedure, it does not show the real structural behavior. This paper presents the seismic analysis of typical steel framed structure including the influence of real joint stiffness. In the first part of analysis the real rigid joints have been introduced, but in the second part the analysis of frames with semi-rigid joints will be presented.

A typical example of the steel framed structure is a Swedish model [1] which is composed of steel frames with a reinforced concrete core. The columns and beams are made of H profiles. In order to achieve more slender structure, the reinforced concrete core is in these analysis replaced with steel bracing as shown in Fig. 1. a) and b).

![Fig. 1. Axonometric view of Swedish model with a) reinforced concrete core; b) steel bracing](image)

The aim of this paper is to show the difference between results obtained from analysis according to Eurocode 8-1 (nonlinear static N2 method) [2, 3] including the previously mentioned joint stiffness (rigid and semi-rigid) for absolute and relative displacements of stores.

In order to take into account the real joint behavior in seismic analysis, numerical simulation of beam-to-column joints were carried out firstly.

1 FINITE ELEMENT MODELLING OF SEMI-RIGID JOINT

1.1 Description of the model

Numerical model is based on a 3D materially nonlinear analysis using the finite element software ABAQUS 6.12. Eight-node solid element C3D8R is used in the modelling of the beam, column and welds. Detail of the geometry and mesh are shown in Fig. 2. a). The finite element mesh was more refined near the welds. Two types of steel were considered, one for the beam and column and another for the welds. Stress and strain response for first material was taken to be nonlinear, and for the second to be bilinear with Young’s modulus of 210000 MPa. Stress and strain relationship for nonlinear behavior is presented in the Fig. 3. According to experimental tests presented in [4] type of structural system is presented in the Fig. 2. b). The model was analyzed for the effect of the bending moment. Bending moment was simulated as a force applied at 1000 mm distance from the joint center (or 850 mm from connection) which acts on the upper side of the top flange of the beam. The load was modelled as 14 concentrated forces which linear growth through the 22 steps. The total force value in the last step was 140 kN.
1.2 The results of FE analysis

During the load action on the finite element model, deformations of beam and column were occurring. Initial and deformed shape is shown in the Fig. 4.a. Total rotation of joint (Rot \( b \)) can be calculated from vertical displacement \( \delta_1 \) in the point beneath the load action as shown in Fig. 4.b. Rotation of connection \( \phi \) was calculate from Eq. (1).

\[
\phi = \text{Rot } b - b_{el} - \text{Rot } H1
\]  

(1)

where \( \text{Rot } b \) is the total rotation of joint with elastic beam rotation \( b_{el} \) which was calculating by Eq. (2),

\[
b_{el} = \frac{\delta_1}{\delta_{50}}
\]  

(2)

\( \text{Rot } H1 \) is the elastic beam rotation which was calculate by Eq. (3),

\[
\text{Rot } H1
\]
where $\delta_1$ is the vertical displacement in the point beneath the load action.

$$b_{el} = \frac{FL_F^2}{2EI_b}$$

(3)

where $F$ is the concentrated forces,

$L_F$ is the distance between load and external column surface which is connected for a beam,

$E$ is the Young’s modulus,

$I_b$ is the moment of inertia.

$$\text{Rot } H1 = \frac{\delta_2 - \delta_3}{z}$$

(4)

where $\delta_2$ and $\delta_3$ are horizontal displacement of column flanges due to shear action obtained from Fig. 2. a).

Final results are shown in the moment-rotation curve in Fig. 5.a). Initial rotational stiffness is considered as 6465.5 kNm/rad. According to Eurocode 3 [5], here obtained stiffness of joint belongs to the semi-rigid zone as shown in the Fig. 5. b). Nonlinear moment-rotation curve is idealised by three-linear curve according to [6] for the seismic analysis purpose.

![Fig. 4. a) Initial and deformed shape of joint; b) Total rotation of joint](image)

![Fig. 5. a) Moment-rotation curve for semi-rigid joints; b) Classification of joints by stiffness](image)
2 THE NONLINEAR STATIC SEISMIC ANALYSIS

In this section the impact of rigid and semi-rigid welded joints on the seismic behavior of the steel framed structure using a nonlinear static analysis approach (N2 method) is presented. This analysis was computed for one frame in the longitudinal direction only.

The seismic demand was computed with reference to the Eurocode 8 [2, 3] response spectrum (Type 1, soil type B, $a_g = 0.254g$ and damping ratio $\xi = 4\%$). In the first case of frame analysis which uses the beam-to-column joints as perfectly rigid (traditionally way), the structure was calculated according to “shear building” criteria [7]. The second case of the frame analysis which uses the beam-to-column joints as semi-rigid in which the rotation of stores are taken into account. To reduce degrees of freedom of structure with semi-rigid joints, i. e. to reduce the stiffness matrices order the static condensation procedure is performed [7].

Fig. 6 shows the position of fundamental period for steel frame with rigid and semi-rigid joints on the elastic response spectrum curve. The base shear-top storey displacement relationship (capacity curve) was obtained by gradually increasing the lateral forces triangular distributed over the stores (pushover). Pushover analysis was performed in SeismoStract software Version 6. The capacity curve was transformed into capacity curve of equivalent single-degree-of-freedom (SDOF) system and was idealized as bilinear curve according to “equal-energy” concept [8, 9]. Fig. 7 shows the capacity curve obtained from pushover analysis for steel frame with rigid joints and semi-rigid joints.

![Graph of fundamental period on the elastic response spectrum for steel frames with rigid joints (dashed line) and semi-rigid joints (dotted line)](image1)

![Graph of capacity curve obtained from pushover analysis for steel frame with rigid joints (dashed line) and semi-rigid joints (dotted line)](image2)
Target displacement for the SDOF system for steel frame with rigid joints amounts to 7.4 cm and for frame with semi-rigid joints amounts to 11.3 cm. If these values are transformed back into the MDOF system (3 DOF), 9.5 cm for steel frame with rigid joints and 14.5 cm for frame with semi-rigid joints are obtained. The steel frame is again subjected to lateral load but now for the value of the target displacement. Finally, results of the absolute and relative storey displacement was obtained, which is shown in the Table 1. and Fig. 8. a) and b).

<table>
<thead>
<tr>
<th>Number of storey</th>
<th>Height of storey [m]</th>
<th>Absolute storey displacement [cm]</th>
<th>Relative storey displacement [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel frame with rigid joints</td>
<td>Steel frame with semi-rigid joints</td>
<td>Steel frame with rigid joints</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>9.5</td>
<td>14.5</td>
</tr>
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</tr>
<tr>
<td>1</td>
<td>3</td>
<td>4.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Fig. 6. a) Absolute storey displacement of steel frame with rigid joints (dashed line) and semi-rigid joint (dotted line); b) Relative storey displacement of steel frame with rigid joints (dashed line) and semi-rigid joint (dotted line)

3 CONCLUSION

The focus of this study was to determine and compare the absolute and relative displacement of steel framed structures with rigid and semi-rigid joints subjected to seismic action. For the analysis with semi-rigid joints, “real” behavior of joints obtained by numerical analysis using finite element method in Abaqus software were taken into account. The steel frame was analyzed for nonlinear static method (pushover) by using SeismoStruct software. Taking into account the real stiffness of semi-rigid joints in seismic analysis, the absolute and relative displacement was increased in regard to results for steel frame with rigid joints, i.e. the absolute top displacement of the steel frame with semi-rigid joints were grater for 52.6 % in regard to steel frame with rigid joints. Maximum relative displacement for the steel frame with rigid joints is on the first storey, while for the steel frame with semi-rigid joints decreases on the first storey and increases on the other stories. The third storey shows the largest deviation for the 130 %.

Joint stiffness plays the important role in the design of semi-rigid frames. The semi-rigid joints cause the large increase of relative displacements of stores over the rigid joints. Analysis of frames with semi-rigid joints resulted in reduction of the beam and column end moments and thus reduce the beam and column cross section. In that way the semi-rigid joints create lighter and more economical frame. Future plans are to develop the simple procedure for steel structure which will take into account semi-rigid joints by means of correction factors.
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REFERENCES


