

THEORETICAL AND EXPERIMENTAL RESEARCHES OF RIGID AND SEMI-RIGID BEAM-COLUMN CONNECTIONS

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Abstract: In this paper is presented theoretical and experimental researches of the steel beam-column connections. 8 types of specimens were being researched made of rigid and semi-rigid connections from which 4 connections are with IPE - profile and 4 connections with tube's section for the beam. From the numerical analysis of the researched models, and specially from the experimental testing in the laboratory for structures in the Faculty of Mechanical Engineering - Skopje, specific interesting conclusions that are ought to have theoretical and practical usage for researchers in this subject for the further researches are received.

Keywords: rigid, semi-rigid, beam - column connections, design (structural design), bending moment, rotation, plastic hinge, collapse

1. Introduction

The behavior of the beam-column connections in the multi-storey frame structures (MSFS) is viewed as a whole and it's in the direct correlation and dependence with the behavior of their main constructive fundamental elements (steel beams, columns and the elements for their connection). In other words, that is the way the beams, the columns and their elements of connection behave, that way the MSFS behaves i.e. the connection between the steel beams with the steel column [2].

The behavior of the beam-column connection in the MSFS depends mostly from their constructive solution. However, dominant in the paper was the research of new or modified constructive solutions of the connections, and all with the purpose of improvement of their loading capacity in conditions of real external loadings. With some constructive solutions the dissipation of energy can be regulated, by controlling the stress and deformational distribution in the sections from the elements of the MSFS i.e. the constructive solution in the connection directly influences the appearance of the plastic hinges in some of the sections from the elements, when their loading is exhausted.

2. Types of researched models -numerical design

For numerical design of the nonlinear answer of the 8 types of models (SP1, SP2, SP3, SP4, SP5, SP6, SP7 and SP8) were used nonlinear programs DRAIN-2DX and ANSYS Workbench [5].

MODEL-SP1 (Fig.1) is a modification of the standard and most commonly used rigid beam-column connection with a final end-plate welded with angled welds at the end of the beam. The modification is used in the additional triangular webs at the end of the beam that are welded to the upper and the lower level with the end-plate, so that the stiffness in the end of the beam is enhanced, same as the loads of the welded beam-column connection of the plate [2]. This is the hot rotated beam (according to DIN1025) IPE200 [3], with height $h=200$ mm, width of the level $b=100$ mm, thickness of the web $t_w=5.6$ mm, and thickness of the levels $t_p=t=8.5$ mm. The material of the beam is S275 JO+M according to EN10025-2/2004 with the following mechanical characteristics: $f_y=\sigma_T=ReH=338$ (MPa), $f_u=\sigma_m=Rm=464$ (MPa), $A=33.1\%$ [4].

The connection between the steel beams (designed by the valid standards MKS (JUS) U.E7.140 correlated with EC3) was made by the modified beam-column connection with the help of the end-plate connection that was welded at the end of the beam. At the end-plate were made 2 holes ($d=17$ mm.), deployed in 4 rows, total 8 holes in one plate i.e. on one beam-column connection. For connecting the beams through the end-plates with the columns, high valued bolts M16 class 10.9, stretched at the right moment ($M_u = 253$ Nm) were used.

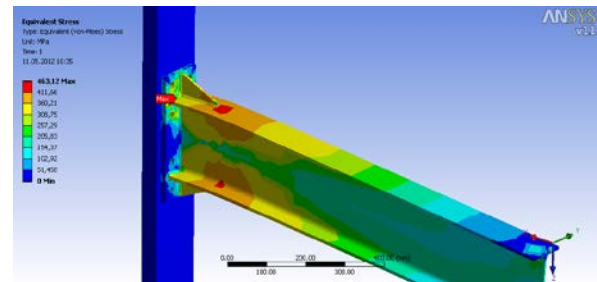


Fig.1 The stress distribution in MODEL-SP1

In the upper image the stress distribution is shown and it is clearly visible that the influence in the welded triangular webs is big i.e. the maximal stress is moved from the end-plate through the middle of the beam i.e. from the end of the beam to the top of the triangular webs. In the place where the maximal stress is in the pressed layer, the appearance of the plastic hinge is expected because of the stability problem in the lateral buckling [MKS (JUS) U.E7.101 – for calculating the lateral buckling in the beam]; or the appearance of the stability problem of the buckling in the pressed part of the web of the beam (MKS (JUS) U.E7.121– for calculating the buckling of plates) [1].

MODEL-SP2 (Fig.2) is a designed rigid beam-column connection with end-plate welded with angular welds at the end of the beam. Same as the previous model, in this connection 2 triangular webs at the end of the beam are used, that are welded to the upper and the lower part of the tubular beam with the end-plate, so that the stiffness of the end of the beam is enhanced, same as the loading of the welded beam-column connection in the plate. The beam in the SP2 model is a hot shaped hollow profile with rectangular cross-section (according to DIN59411, JUS C.B5.213) [] 200.100.5, with height $h=200$ mm, width of the level $b=100$ mm, thickness of the walls in the section $t_s=5$ mm. The material of the beam is S355J2H according to EN10219-1/2006/EN10021 with the following mechanical characteristics: $f_y=\sigma_T=ReH=437$ (MPa), $f_u=\sigma_m=Rm=554$ (MPa), $A=24.8\%$.

For the design of the beam our valid standards MKS (JUS) U.E7.140 (in correlation with EC3) were used, adapted for the shape of the beam. Here, same as the previous model, end-plate connection is used with a bigger height than the one of the SP1 model, as a result to the specific shape of the beam (rectangular cross-section), welded at the end of the beam. In the final plate 2 holes ($d=17$ mm) were made, deployed in 4 rows, total 8 holes on one plate i.e. on one beam-column connection. For connecting the beams through the final plates with the columns (on the column levels, holes with the same pattern and number as the end-plates were made), with bolts M16 class 10.9.

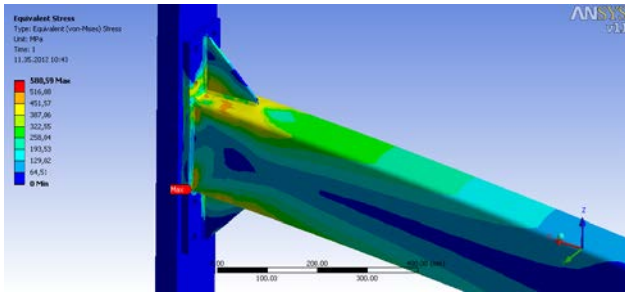


Fig.2 The stress distribution in MODEL-SP2

In the upper image in which the stress distribution and the influence of the welded triangular webs is shown i.e. the maximal stress that is moved from the final plate to the middle of the beam; in the end of the beam to the top of the lower triangular web [1].

MODEL-SP3 (Fig.3) is a designed rigid beam-column connection with an ending joint that is welded to the dismantling connection on the beam with the column. The joint is made by welding 3 plates under an angle of 90° to the background plate, where holes for the connection with the beam and the connection with the column were made. The design of the joint is made so that its loading is bigger than the loading at the end of the beam, thus the relocating of the eventual plastic hinge will be on a bigger distance from the column, different from the previous 2 analyzed models. The loading of the joint depends from: W_x – the modulus of section receiving the bending moment, A_r – surface of the web for receiving the cutting (shearing) and the mechanical characteristics of the adopted material.

On the beam IPE200 holes are made i.e. 2 in the levels and 3 on the web, total 7 bolts for the connections on the beam with the joint. For bigger beams, the number of bolts in the levels and webs can increase. Important for the design on this model is the loading of the bolts in the levels which are different from the ones for the connection of the joint with the column, which are mainly loaded under shear. Depending on their projected loading capacity in correlation with the loading capacity of the joint and of the beam, the order of elements failure contained in the connection (the mechanism of collapse) can be predicted. With the model SP3 precision is needed during the construction of the joint and making holes for the bolts on the joint and the end of the beam, same as the setting pattern of the bolts during the construction of the beam.

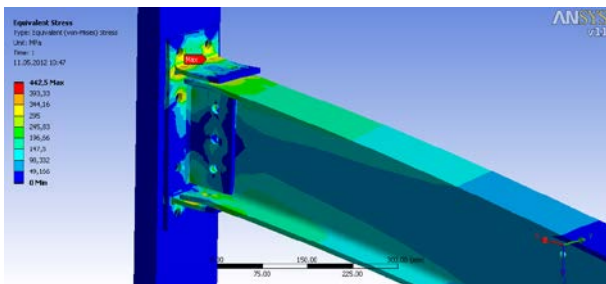


Fig.3 The stress distribution in MODEL-SP3

In the MODEL-SP3 the maximal stress, appear in the horizontal angular welds of the joint, but those, same as the elements of the joint, are designed with bigger static sizes in the end of the beam, so that they aren't a danger for collapse of the connection. Relatively smaller are the stresses, but still big enough in the place of the connection in the levels on the beam, with the joint, same as the connection between the web with the vertical web in the joint. The forces from the bending moment at the end of the beam are expected to cause stretching in the tightened level and an eventual buckling in the pressed level, if it didn't come to appeasement in the leveled screws that are exposed to cutting (shearing) at the beginning. The further development can go into a direction of defining the exact correlations of the geometrical and static characteristics at the end of the beam, the number and the diameter of the means of connection (bolts) and the dimensions of

the joint, everything for the purpose of getting a controlled collapse mechanism of the connection [1].

MODEL-SP4 (Fig.4) is a designed rigid beam-column connection. The connection of the beam (IPE200) with the column is made only by the levels of the beam, throughout before made joints, one for each of the levels of the beam. The joints can be made from hot rolled or welded L-profiles depending from the needed thickness, with welded triangular web in the middle of its strengthening zone. The connection of the joint with the level of the beam is made with 4 bolts, or total of 8 bolts on the two of the levels of the beam. The joints are design so that their loading capacity is bigger than the loading capacity at the end of the beam and the eventual collapse would appear in the assets of the connection of the beams. The connection in each of the joints with the column is made with 4 high valued bolts class 10.9, strained at the desirable moment. These bolts are designed so that they would not fail during the most extreme loadings of the connections i.e. the collapse of the connection would take place at the end of the beam, in the joint, in the assets for the connection between the beam and the joint, but not in the elements of the connection (bolts).

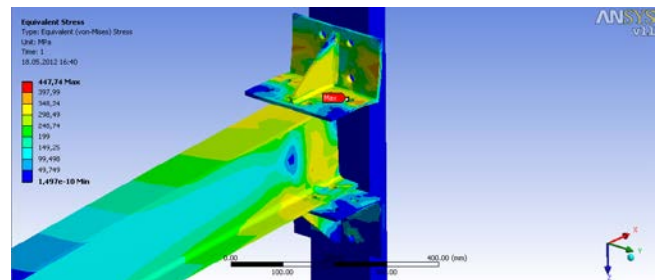


Fig.4 The stress distribution in MODEL-SP4

In the MODEL SP4 the maximal stress appears in the vertical angular welds on the joint and in the levels in the beam in the place of the connection with the joint. Because the joint (same as in the SP3 model and the rest of the models where a joint is used) is designed with big static sizes at the end of the beam, the maximal stress does not represent a danger for collapse of the connection. The forces from the bending moment in the end of the beam is expected to cause stretching in the tightened level and an eventual buckling in the pressed level, if does not come to appeasement in the leveled screws that are exposed to cutting (shearing). In this model, different from the previous SP3 model, this influence is emphasized as a result of the type of the connection that was made only through the levels of the beam, and not through the web which was the case in the SP3 model [1].

MODEL-SP5 (Fig.5) is a designed rigid beam-column connection. The connection between the beam (200.100.5) and the column is made through 2 already prepared and welded horizontal plates at the end of the upper and the lower part of the beam that are additionally strengthened with 2 vertical webs. On the plates holes are made together with the holes on the already made joints. The dimensions of the joints are same as the ones in the SP4 model, however in this model exterior (the furthest) holes are used for the joints of the connection with the horizontal plates at the end of the beams; the joints can be made from hot rolled or welded L-profiles depending on the needed thickness, with a welded triangular web in the middle of its strengthening zone. The connection between the joint and the plates that are at the end of the beam is made with 4 bolts, or total of 8 bolts for one beam. The joints are designed so that their loading capacity is bigger than the loading capacity of the beam and the eventual collapse would happen in the assets of the connection between the joints and the beams after some plastic deformations at the end of the beams occurs. The connection between every joint and column is made with 4 high valued bolts class 10.9, strained at the desirable moment. These bolts are designed so that they does not fail during the most extreme loadings in the connections i.e. the collapse of the connection would take place at the end of the beam, in the joint.

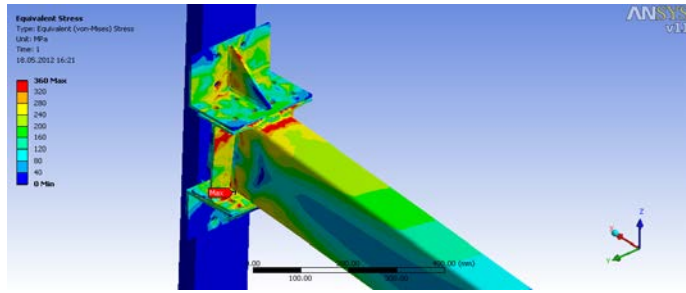


Fig.5 The stress distribution in MODEL-SP5

The forces from the bending moment in the end of the beam is expected to cause stretching in the tightened level and an eventual buckling in the pressed level, if does not come to appeasement in the leveled bolts that are exposed to cutting (shearing). In this model this influence is emphasized as a result to the connection that was made only through the levels of the beam, and not through the web that was the case in the SP3 model [1].

MODEL-SP6 (Fig.6) is a designed semi-rigid beam-column connection. The connection between the beam and the column is made only through the web in the beam (3 bolts) and the final welded joint. The welded T-joint is dismantling connected with the column with total of 4 high valued bolts 10.9. The joint is made by welding the 2 plates under an angle of 90° , where already were made holes for the connection with the web of the beam and the connection with the column. The design of the joint is made so that its loading capacity is big enough so that the eventual collapse would appear at the end of the beam i.e. the beam-column connection. On the beam IPE200 3 holes are made on the web for the T-joint. For bigger beams, the number of bolts on the web can increase.

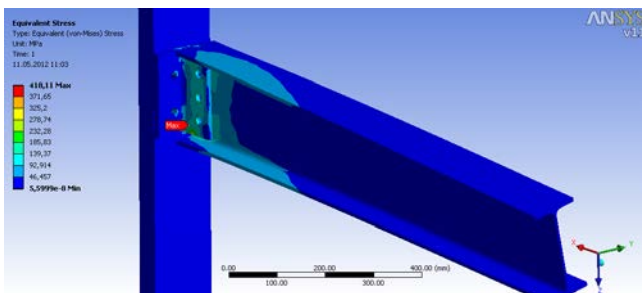


Fig.6 The stress distribution in MODEL-SP6

In the MODEL SP6 the maximal stress, appears at the web of the beam to the final (upper and lower) screws and accordingly to the vertical welded plate of the joint. According to this, the joint, and its vertical plate which binds the beam, are designed with bigger static characteristics than the web of the beam. The fail of the connection is expected in the web of the beam as a result of the stretching and cutting of part of the web next to the hole in the upper bolts or as a result of the cutting (buckling) of one of the external (upper or lower) bolts [1].

MODEL-SP7 (Fig.7) is a designed semi-rigid beam-column connection. The connection between the beam and the column is made through the temporary end of the beam and the final welded T-joint with the help of total 3 bolts. The welded T-joint is dismantling connected to the column with a total of 4 high valued bolts class 10.9. The joint is made by welding the 2 plates under an angle of 90° , where already were made holes for the connection in the web of the beam and the connection with the column. The design of the joint is made so that its loading capacity is big enough so that the eventual collapse would appear at the end of the beam i.e. the beam-column connection. On the beam (I 200) is welded a steel plate with transverse web on which 3 holes are made for the connection with the T-joint. For bigger beams, the number of bolts on the web can increase.

This design of the connection would be an answer to the previous model (SP6) in case where the beams would be used a

rectangular hollow section instead of an open I-section. This is a quashing connection because it takes a specific bending moment followed by movements. The eventual collapse would appear firstly in some of the ending bolts that are the most loaded and where a superposition of the cutting forces appears from the transversal shearing force and the forces from the receiving bending moment.

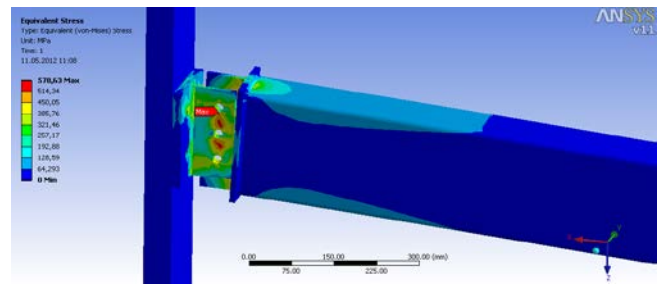


Fig.7 The stress distribution in MODEL-SP7

In the MODEL SP7 the maximal stress, appears in the web of the beam, next to the holes for the screws and accordingly to the vertical welded plate of the joint. Also, big stress appears in the welds from the joint same as at the end of the beam and it's upper and lower part next to the welded plate. Because of this, the joint is designed with bigger static characteristics at the prepared end of the beam. The collapse of the connection is expected in the part of the beam as a result of the stretching and cutting in the vertical part of the plate next to the hole in the upper screw or as a result to the cutting (buckling) of one of the external (upper or lower) bolts [1].

MODEL-SP8 (Fig.8) is a designed semi-rigid beam-column connection. The connection between the beam and the column is realized with 3 long bolts between the end of the beam and the final welded U-joint. The welded U-joint is dismantling connected to the column with the total of 4 high valued bolts class 10.9. The joint is made by welding the 3 plates under an angle of 90° , where already were made holes for the connection with the web of the beam and the connection with the column. The design of the joint is made so that its loading capacity is big enough so that the eventual collapse would appear at the end of the beam i.e. the beam-column connection. On the beam (I 200) 3 holes are made for the connection with the U-joint. For bigger beams, the number of bolts on the web can increase.

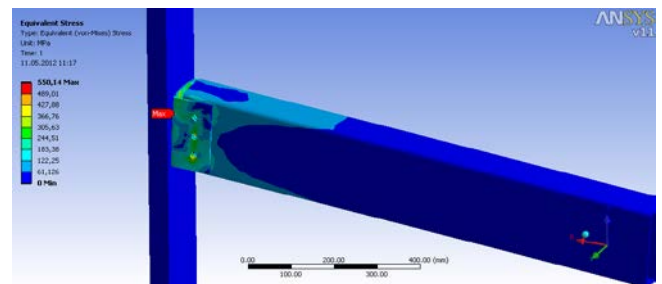


Fig.8 The stress distribution in MODEL-SP8

In the MODEL SP8 model the maximal stress, is in the welds from the U-joint for the connection between the beam and the column (reactivity wall), but the same are designed so that a danger of collapse does not exist. Also, the bigger stress appears in the holes of the longer bolts, as in the longer bolts itself. Because the joint is designed with bigger static characteristics in the end of the beam, the collapse of the connection is expected in the part of the beam as a result of the cutting in the vertical part of the beam next to the hole and in the upper bolt a result of the cutting of one of the external bolt [1].

3. Experimental researches

The experimental testing of the 8 of the designed models is completely done in the Laboratory for Structures in the Institute for Welding and Welded structures in the Faculty of Mechanical engineering in Skopje. As a final result from the experiments are

the characteristic diagrams: F- ΔL (force-displacement) and M- Φ (bending moment-rotation in the end of the beam) (Fig.12) [1].

The equipment for adding and transferring the force contains one axial press (piston) that is placed vertical on the steel frame in the experimental desk which presses the end of the consul omission through the force sensor, causing negative bending moment and shearing in the connection in the end of the beam (Fig.9).

For every model (SP1, SP2, SP3, SP4, SP5, SP6, SP7 and SP8), a loading diagram was previously made, through adding the displacements. The process was made by adding the displacements, and not adding force, because in nonlinear conditions, when it comes to reducing the force, leading an experiment by adding force is practically uncontrolled and it may come to sudden collapse of the model. Adding the increased displacement at the end of the console overhang of the beam through the piston of the researched device was made gradually only in one direction until the total capacity was used from each of the models and their failure happens. In the following images is presented the research for each of the models in different faze of the testing:



Fig.9 Model SP1 was set for quasi static research/ appearance of the plastic hinge (stability problem-lateral buckling)



Fig.10 Model SP5/Appearance of the plastic hinge (stability problem-buckling in the lower pressed part of the beam)



Fig.11 Model SP8/ Collapse of the connection as a result to plastic deformations to cutting the end of the beam in the upper long bolt

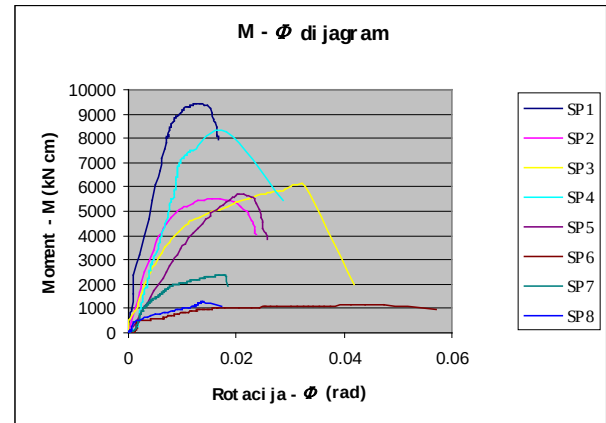


Fig.12 M- Φ diagram for all of the 8 models (experimental analysis)

4. Conclusions

During the designing of the beam-column connections under the influence of the horizontal loading (seismic loading, loading under strong winds), very important factor is the control of the weight, stiffness, strength and the ductility of the material of the elements from which depends directly the behavior of the elements in the connections, and by that and the behavior of the models structure; it is proved that many of the collapses of the models that happened were a result of the used rigid materials [2].

From the comparative *experimental analysis* of all of the 8 models can be concluded that the capacity of the loading of the bending moment in the models with rigid connection (SP1, SP2, SP3, SP4 and SP5) is significantly bigger than the one with the semi rigid connections (SP6, SP7 and SP8), which was expected; if the rigid connections are separately analyzed (SP1, SP2, SP3, SP4 and SP5), the model SP1 has the biggest capacity to carry the bending moment over the others, but in the other hand the smallest rotating capability (plastic deformability) over the other 4 i.e. the 7 models with the semi rigid connections (SP6, SP7 and SP8); the model SP3 has the biggest rotating capability over the other 4 models with the rigid connections (SP1, SP2, SP4 and SP5); the deformation (rotation) capability in the researched models is inversely proportional from the loading capacity of the beam i.e. the semi rigid connections have bigger plastic deformability and possibility for bigger rotation, but they have smaller loading capacity compared to the ones with rigid connection.

The main idea and direction for further researches is obtaining one "ideal" beam-column connection that in the same time will have relatively high strength and deformational characteristics i.e. loading capacity for bigger bending moments and bigger rotating capability in the same time.

5. Literature

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