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Numerical modelling of stress and deflection behaviour for welded steel beam-column

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Abstract: In this study, stress and deflection behaviours of T-type welding joint applied to HE200M steel beam and column were investigated in finite element method (FEM) under different distributed loads. In the 3D-FEM modelling, glue option was used to contact between steel materials and weld nuggets. Geometrical model was designed as 3-dimensional solid in ANSYS software program. After that, homogeneous, linear and isotropic properties were used to design to materials of model. Solid-92 having 3-dimensional, 4 faced and 10-noded was selected as element type. In consequence of mesh operation, elements of 13285 and nodes of 28086 were occurred. Load distribution was applied to top surface of steel beam to determine behaviours of stress and deflection. As a result of FEM analysis applied with the loads of 55,000 N, 110,000 N and 220,000 N, maximum values were obtained as 116 N/mm^2, 232 N/mm^2 and 465 N/mm^2 for stress and obtained as 1,083 mm, 2,166 mm and 4.332 mm for deflection, respectively. When modelling results and classical calculation values were compared, it was obtained difference of 10 % for stress values and 2.5% for deflection values.

Keywords: steel beam and column; modelling; finite element method; stress; deflection.

1. Introduction

Steel construction has been used for a long time in the construction industry. Nowadays, it is applied to an important area which is carrying great earthquake risk for the purpose of safety building construction. The steel constructions have a lot of advantages as resistance, lightness, mass production, sensitiveness, easiness of control, cost, maintenance-restoration, removable and freedom design (Hattap *et al.* 2005, Kayhan *et al.* 2010, Callister 1993). Welded, bolted and riveted methods are used to combine of these constructions. Welding joint method is widespread and one of the important applications in the steel constructions. To determine performance of welded steel construction should be found out some behaviour as stress, strain, carry-load capacity, the adequacy of joint, deformation and deflection effect on load. Engineering calculations and experiments methods are used to obtain some properties of steel construction. Unfortunately, these techniques have a long time and high cost. To cope with disadvantages, computer aided modelling techniques are propagated. Modelling techniques make simplicity for calculations. Also, there are no a long time and high cost for establishing model (Deren 1995, Karaduman *et al.* 2002).

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Computer aided modelling and simulations have become a useful part of mathematical modelling of many systems in physics, astrophysics, chemistry, biology, materials science, structural, construction and engineering. Modelling and simulations can be used to explore and gain new insights into new technology and to estimate the performance of systems too complex for analytical solutions by companies and universities. (Strogatz 2007). For example, 70% of total personal has been working with regard to modelling and simulation at Center of Advanced Vehicular systems (CAVs) of Mississippi State University (Findik 2007).

The finite element method (FEM) which can be used by computer aided modelling has become one of the most important and useful tools for scientists and engineers over the last two decades. The finite element method is a powerful technique originally developed for numerical solution of complex problems in structural mechanics, and it remains the method of choice for complex systems (Stolarski *et al*. 2006, Moaveni *et al*. 2008, Kim *et al*. 2009). This method were used a lot of studies for investigation of static and dynamic of materials as pipe, beam, column and others. In the FEM, the structural system is modelled by a set of appropriate finite elements interconnected at points called nodes. Elements may have physical properties such as thickness, coefficient of thermal expansion, density, elastic modulus, shear modulus and Poisson's ratio.

A paper (Fricke *et al*. 2001) was published that the technique developed for numerical simulation of the welding process had not only been properly verified and validated on austenitic pipe welds, but that it also permitted making selective statements on improvements to the welding process. In a modelling study (Raymond *et al*. 2004), finite element analyses of standard tailor-welded blank forming tests was performed to determine the effects of weld modelling techniques on simulation results. Results indicated that there were a number of relatively subtle effects associated with the manner in which the weld line is modelled. Most of these effects relate to the constraining effect of the weld line with respect to strain along the axis of the weld line. A study (Zhang *et al*. 2000) was presented a computational model to predict residual stresses in a girth weld of a core shroud. The girth weld was a multi-pass submerged-arc weld that joins two types of 304 austenitic stainless steel cylinders. The analysis results were obtained from these studies shed light on the residual stress characteristics in core shroud weldments and the effects of residual stresses on stress corrosion cracking behaviour. In a study (Sarkani *et al*. 2000) was investigated in the residual stress fields in a welded T-joint, comparing computed by 3D models with computed by 2D models. The residual stresses in the plane of the 2D model were computed by finite element method showed fairly good agreement with those computed by the 3D model.

An analysis (Lie *et al*. 2001) was described a systematic method in a paper of modelling the weld thickness of a tubular Y-joint. Some tubular welded specimens are fabricated, and the outer weld beams were measured physically. It was shown that scale factors and constants were adequate to satisfy the required minimum outer weld beam. Therefore, the proposed method to model the weld size was both consistent and accurate for any tubular Y-joints. In the stress analysis study (Pang 1993) was showed that a wide combination of weld angles and toe radii are possible. In a measurement of actual weld toe beams experimental and finite element analysis of stress concentration and stress distribution was carried out for a particular cruciform welded joint. Stress intensity factor calculations using closed-form integration and weight function methods were carried out for weld toe cracks. In the bi-steel study (Clubley *et al*. 2003) was evaluated a system of double skin steel-concrete-steel construction. The experimental and numerical analysis of the shear strength of each friction weld subject to push out load was discussed. Finite element analysis using nonlinear discrete element models was been used to examine the local behaviour of concrete filled panels. Conclusions drawn indicated the presence of several possible failure modes in the shear connection.

In a modelling study (Foundoukus *et al*. 2008), the static behaviour of steel beams was simulated using a finite element model. The model was compared to test results showing good agreement. It was then used in parametric studies of transverse shear capacity and uniformly distributed load cases of steel beams. In another study (Sabuwala *et al*. 2005), the behaviour of fully restrained steel connections subjected to blast loads was examined using finite element analysis. The reinforced connection performed better than the un-reinforced connection under blast loads, exhibiting lower displacements, rotations and stresses. A paper (Lien *et al*. 2010) was published with regard to the numerical model was verified by comparing the results with the published experimental and analytical results for steel structures. The analytical results show that the fire response of steel structures is significantly affected by the boundary conditions of the structure and the applied load. A study (Zona *et al*. 2011) was compared three different beam models and relevant finite elements for the non-linear analysis of composite members with partial interaction. Results show that the three models present small differences when composite beams dominated by the bending behaviour are considered. In a numerical study (Kiymaz *et al*. 2010), it was investigated in effect of web openings on the transverse load carrying capacity of steel beams with sinusoidally corrugated webs using finite element program. For the geometries considered in the study, introducing a web opening causes strength reductions between around 15% up to 50%.

The aim of this study is to evaluate modelling of stress distribution and deflection behaviour for welded steel beam and column using computer aided finite element method. After the finite element analysis, a comparison was done between modelling results and classical calculations with regard to stress values and deflection amounts.

2. Finite element modelling

2.1. Materials

HE200M steel beam and column were used to modelling through finite element analysis. Geometrical dimensions and weight of the hot rolled steel beam and column have occurred 206 × 220 × 1,000 mm and 103 kg/m, respectively. Chemical content of the steel beam and column was given in Table 1.

The geometrical shape of steel beam and column can be shown in Fig. 1. Geometrical dimensions of steel beam and column in according with European Structural Steel Standard (EN 10025 2004) were given in Table 2. These structural steels are also widely used as girder stem because of body plane loadings in the steel structures.

2.2. Modelling of materials

In the modelling study, ANSYS software which is a numerical program based finite element method was used to analyse. A steel beam and a steel column were welded with T-weld type for simulation of

Table 1 Chemical content of steel beam and column

Norm	Fe	Mn	Si	C	S	P
DIN EN 10025-94	98,84	0,5	0,4	0,17	0,05	0,04

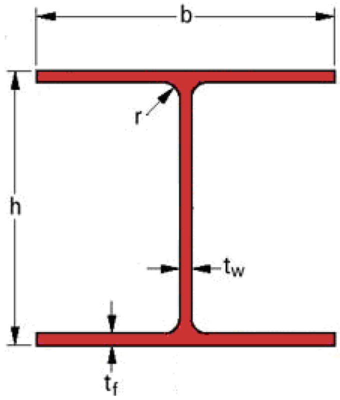


Fig. 1 Geometrical shape of steel beam/column

Table 2 Geometrical dimensions of steel beam/column

Symbol	h	b	t_w	t_f	r	mass of 1 meter
Value	220	206	15	25	18	103
Unit	(mm)	(mm)	(mm)	(mm)	(mm)	(kg/m)

construction. Materials of model were selected as homogeneous, linear and isotropic in the program. After the design of solid model, elastic modulus and Poisson's rate of beam, column and weld nugget were described to program. Steel beam and column has elastic modulus of 210,000 MPa and Poisson's ratio of 0,33. On the other hand, weld nugget has elastic modulus of 271000 MPa and Poisson's ratio of 0,32, these values were obtained by an experimental study (Ay *et al.* 2003). Length of steel beam and column was designed as 1,000 mm. Size of weld nugget which was designed single-run welding was used to geometrical model as 20 mm. Six weld nuggets were totally applied to model together with two outer corners and four inner corners. For simulation of joint between steel materials and weld nuggets, "Glue Option" was used in the ANSYS software program. Geometrical design of welded model is given in Fig. 2.

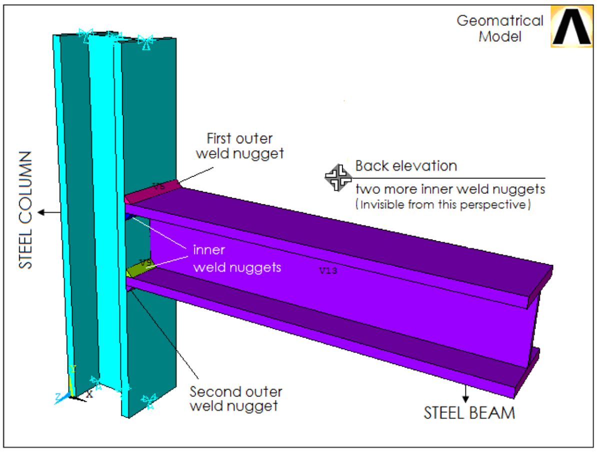


Fig. 2 Geometrical model of welded construction

2.3. Mesh operation

In the finite element model, element type was selected as Solid 92 which has non-linear geometrical character and so high performance in CAD/CAM application is to be similar to real models (Moaveni *et al*. 2008). As shown in Fig. 3, welded model was meshed using SOLID 92 element, character of which is quadratic and 10-noded. At the end of mesh operation, it totally occurred elements of 13285 and nodes of 28086.

2.4. Boundary conditions and loads

In the finite element modelling (FEM), boundary conditions and loads were described to the program. Top and bottom surfaces of steel column were fixed in all direction (x, y and z). On the other hand, different distributed loads of 55,000 N, 110,000 N and 220,000 N were applied to top surface of steel beam. In the modelling, ANSYS Multiphysics module was selected as working format. After FEM model operation, the static analyses were done, and stress and deflection values were determined. Deformation scale also increased 20 times to observe the deflection behaviours more effectively. After the analyses, stress distribution in the beam, column and weld nuggets were illustrated as colourful. Maximum and minimum stress areas were investigated in the model. In Fig. 4, boundary conditions of finished model were illustrated and also, arrows have been demonstrated directions of distributed loads. In Fig. 5, node image was shown together direction of distributed load applied to steel beam and directions of fixation applied to steel column.

3. Results and discussion

3.1. Evaluation of stress distribution

After finite element model was finished, three analyses were applied to steel construction model under the different loads. Values of stress and deflection were determined with these analyses. In Fig. 6(a), it

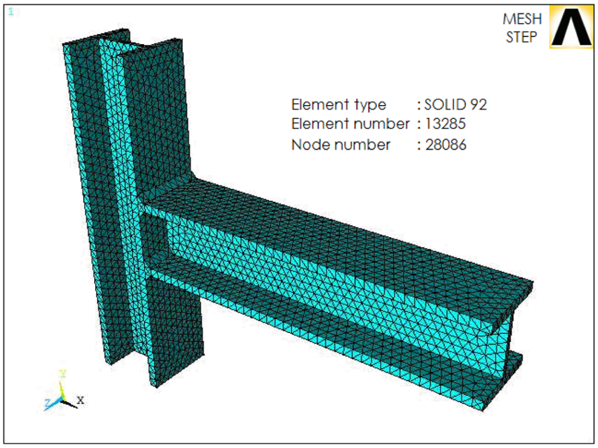


Fig. 3 Mesh model of welded construction

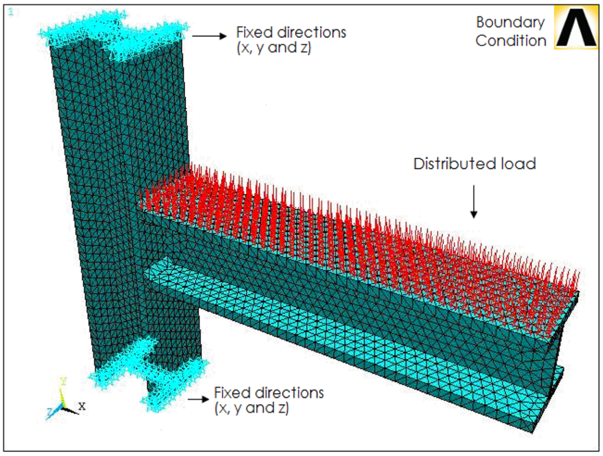


Fig. 4 Boundary conditions and load for FEM model

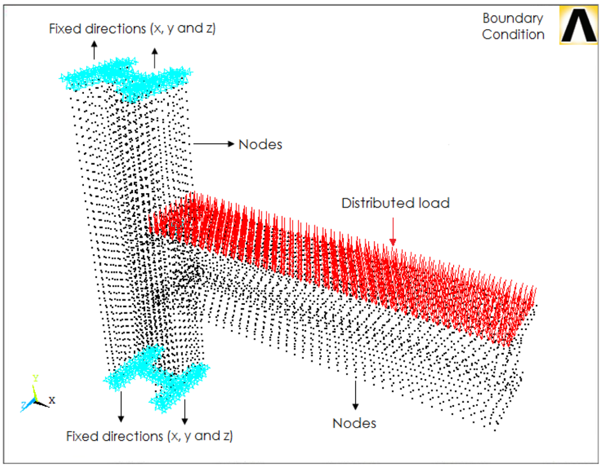


Fig. 5 Node image for FEM model

was shown stress distribution for distributed load of 55,000N. Maximum value of stress was occurred in middle zone of top and bottom of outer weld nugget as 94 N/mm^2.

Stress distributions for loads of 110,000N and 220,000N have been similarly seen in Fig. 6(b) and Fig. 6(c), respectively. The cause of this similarity was linear behaviour indication between loads. Maximum stress value under the load of 110,000N was 188 N/mm^2, as shown in Fig. 6(b), on the other hand, maximum stress value under the load of 220,000N was 376 N/mm^2, as shown in Fig. 6(c), with value scale line. Maximum stress zone for all three analyses, can be seen as an example in Fig. 7, was observed in middle zone of top and bottom of outer weld nugget. While tensile forces were occurring top of above outer weld nugget, compression forces were occurred in the bottom of outer weld nugget in the FEM model. This behaviour has been expecting in the zone of weld nugget. The expected stress zones were occurred in these areas, and so maximum value of stress was obtained in mentioned zones.

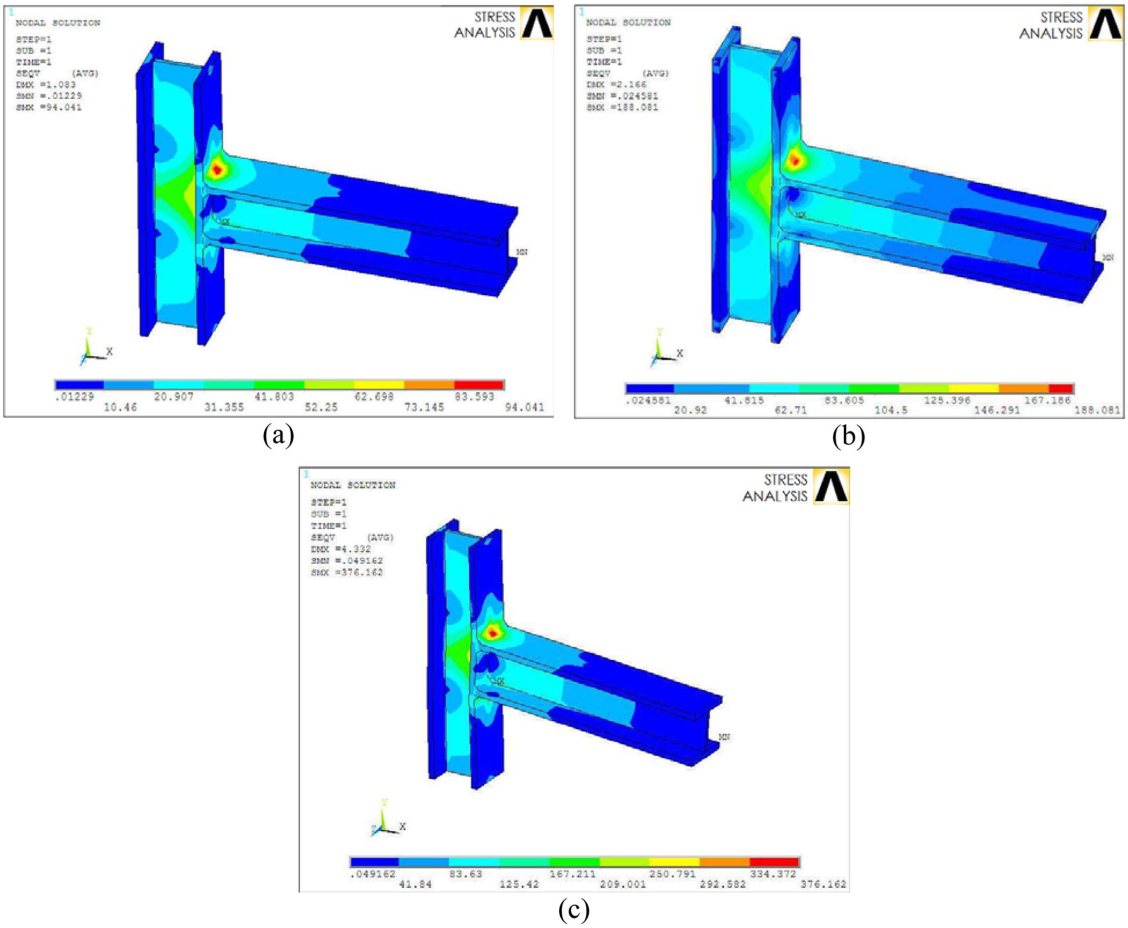


Fig. 6 Stress distribution for loads of (a) 55,000N, (b) 110,000N and (c) 220,000N

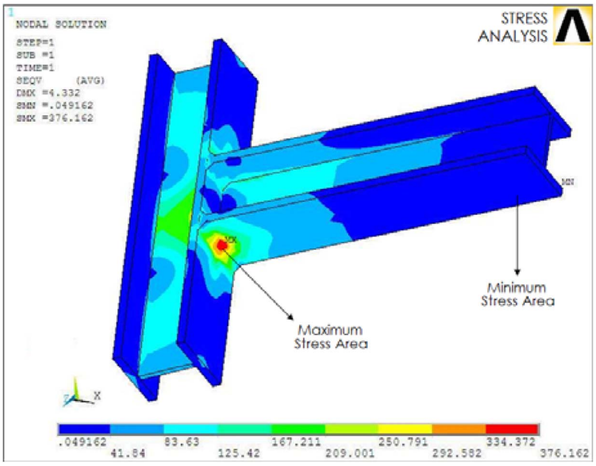
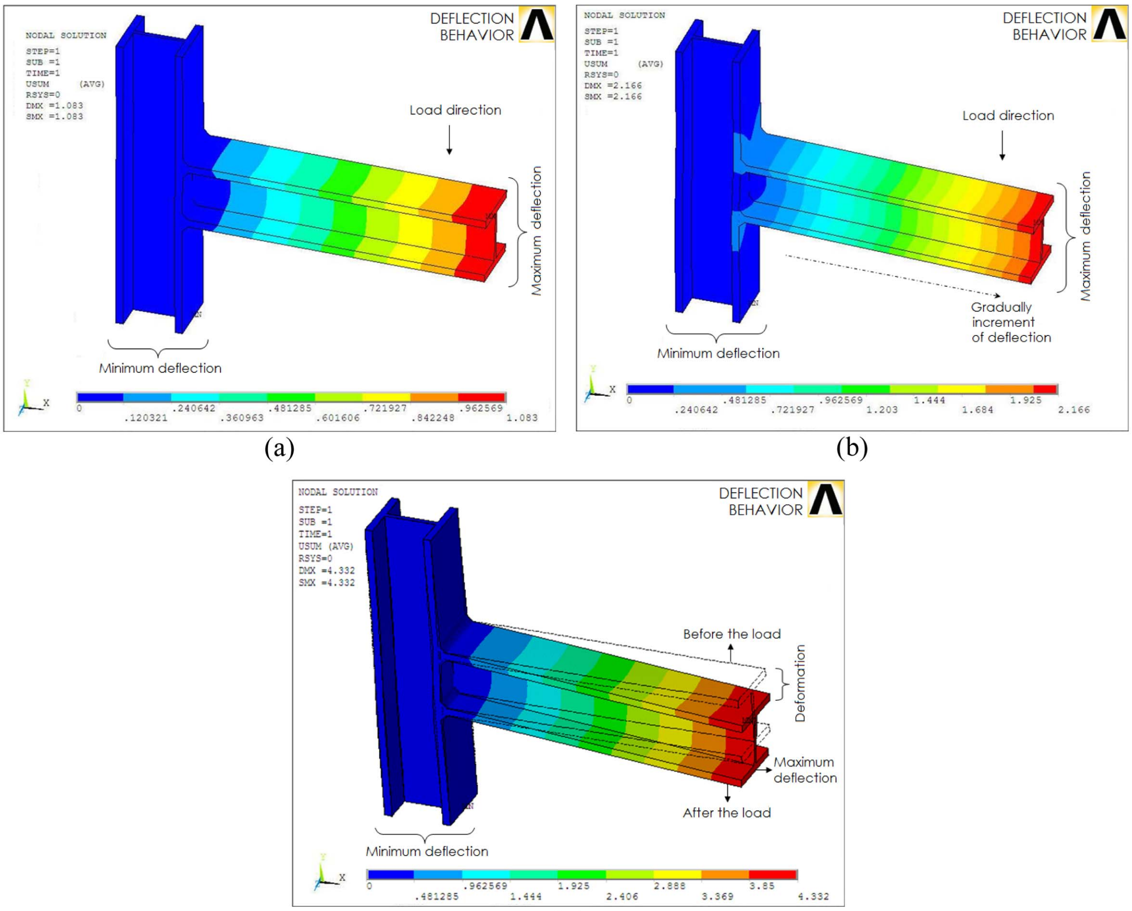


Fig. 7 Maximum and minimum stress area for load of 220,000N

3.2. View of deflection behaviour

Deflection distributions for all analyses were shown in Fig. 8. Maximum deflection values for loads of 55,000 N, 110,000 N and 220,000 N were 1,083 mm, 2,166 mm and 4,332 mm, respectively. Deflection values were linearly increased with the increment of load, similarly stress values. The cause of this similarity was same conditions apart from the load. It showed that the applied load exhibited a strong effect on stress behaviour and deflection variation of steel construction. Minimum deflection area was observed along the whole length of steel column, as clearly shown in Fig. 8(a). On the other side, deflection values for all analyses were gradually increased up to end of steel beam, as obviously shown in Fig. 8(b). In Fig. 8(c), it was illustrated deflection behaviour of steel beam before and after the load. These results reveal that the applied load which was applied to (–) *y* direction forced to bend to steel beam for all construction models. The behaviour of deflection variation in this study is in agreement with the previous experimental study, in which was obtained effect of deflection amount on the load (Soy 2011).



(c)

Fig. 8 Deflection distribution for loads of (a) 55,000N, (b) 110,000N and (c) 22,0000N

3.3. Classical calculations

After finite element analyses were made, stress and deflection values for load of 55000N have been calculated using below theorical formula. In the modelling, maximum stress values for all analyses had been seen on top of welded nugget. In here, stress values of welded nugget where moment effect was calculated according to theorical strength of materials.

The maximum moment (M_{max}) was calculated as

$$M_{max} = P \times L/2 \tag{1}$$

where P is load (N), L is length of steel beam (mm).
Area of weld nuggets (A_w) was calculated as

$$A_w = 2\ [\ (S_w \times b_{oc}) / 2\ ] + 4[(S_w \times b_{ic}) / 2] \tag{2}$$

where S_w is size of weld nugget (mm), b_{oc} is length of outer corner weld nugget (mm), b_{ic} is length of inner corner weld nugget (mm).
Moment of weld nuggets (I_w) was calculated as

$$I_w = [(b_{oc} \times S_w^3) / 12 + A_{oc} \times a_o^2] + [(b \times S_w^3) / 12 + A_{ic} \times a_i^2] \tag{3}$$

where A_{oc} is area of outer corner weld nugget, A_{ic} is area of inner corner weld nugget, a_o is distance from outer weld nugget to gravity center of construction, a_i is distance from inner weld nugget to gravity center of construction.
Strength moment of weld nuggets (W_w) was calculated as

$$W_w = I_w / c \tag{4}$$

where c (mm) is distance from top area to center of gravity, in other words, c is half of h for this construction.
Cutting force (τ_{max}) which was only reacted to weld nuggets was calculated as

$$\tau_{max} = P_1 / A_w \tag{5}$$

where P_1 is load of 55,000 N.
Total stress (N/mm^2) value of weld nugget effect on cutting force and moment was calculated as

$$\sigma_{\mathrm{weld}} = (P_1 / A_w) + (M_{max} / W_w) \tag{6}$$

Deflection value (Δ_{max}) for distributed load of 55000 N was calculated as

$$\Delta_{\mathrm{max}} = W \times L^4 / 8 \times E \times I \tag{7}$$

where W (N) is distributed load, L (mm) is length of steel beam, E (MPa) is elastic modulus I (cm^4) is

Table 3 Calculation results for stress and deflection values

Load (N)	Stress values (N/mm^2)	Deflection values (mm)
55,000	81.30	1.11
110,000	162.60	2.22
220,000	325.20	4.44

inertia moment of steel beam.

The above calculated stress value was occurred in weld nugget for load of 55,000N. On the other hand, it was linearly increased in weld nugget for other load applications. In other words, stress values for loads of 55,000N, 1,110,000N and 220,000N were 81.30 N/mm^2, 162.6 N/mm^2 and 325.2 N/mm^2, respectively. For this reason, all condition and construction model were same as one another from out the load value. In the view of calculations, deflection values for loads of 55,000 N, 110,000 N and 220,000 N were 1.11 mm, 2.22 mm and 4.44 mm, respectively. Calculation results for stress and deflection values were shown in Table 3.

3.4. Comparison of results

A comparison was made between modelling results and classical calculations. When we compared the modelling with classical results with regard to stress values, it has been seen about 10 % difference. As the cause of this, we can say that all weld nuggets were modelled nonporous and faultless together excellent conditions. It shouldn't be forget that modelling works apply to virtual conditions, are not completely real. In Fig. 9, maximum stress values for both classical calculation results and modelling results have been showed. In here, proper correlation has been seen a between classical and modelling results. Approach of stress lines in graph is logical and verified to this study. Although distance of lines with load increment has been opened, stress difference is always about 10% as linear. In the deflection values, it has been seen 2.58 % difference between the modelling and classical results. This rate is

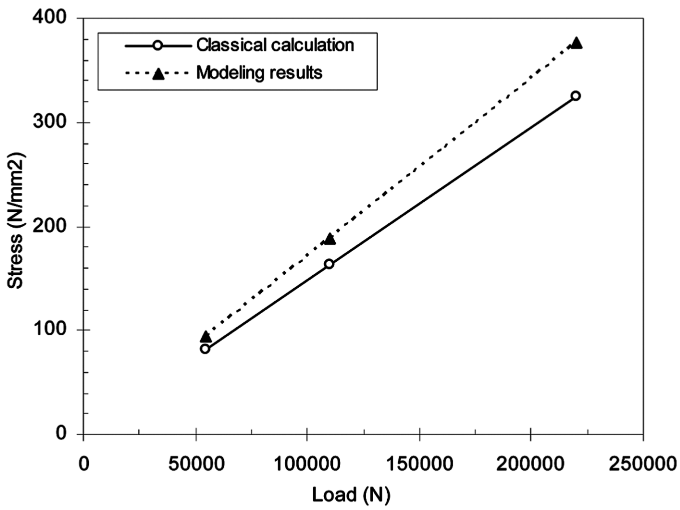


Fig. 9 Comparison of stress values effect on the load

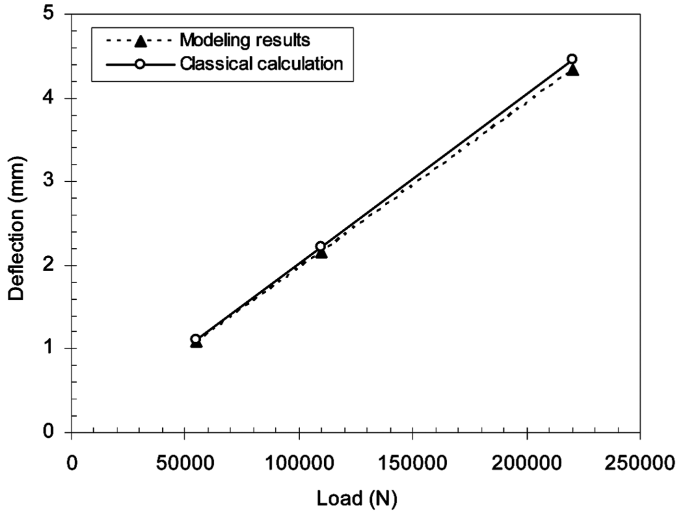


Fig. 10 Comparison of deflection values effect on the load

adequate for logical approach. In Fig. 10, deflection values for both classical calculation results and modelling results have been illustrated.

4. Conclusions

Finite element analyses results and classical calculations were compared each other and obtained as a logical approach by favour of this study. In all analyses, maximum stresses were occurred on top of weld nuggets. On the other hand, minimum stresses were observed in end area of steel beam. Deflection values for both FEM models and classical calculations were gradually increased up to end of steel beam, similarly. Before real application of similar constructions, it can be estimated maximum/ minimum stress area and deflection values using FEM modelling. When we compared the modelling with classical calculation results, it has been seen 10% difference for stress values and 2.5% difference for deflection values. These rates are adequate for logical approach. It shouldn't be forgotten that modelling works are not completely real. Resultant approach from this study can use in industrial applications of steel construction and can suggest a course of action to industrial companies. Also, this study has been emphasized that computer aided modelling can be used together with the real applications.

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