The parameters effect on the structural performance of damaged steel box beam using Taguchi method

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Abstract

In the current study, the influence of notch or opening parameters and the positions of the applied load on the structural performance of steel box beams up to failure was investigated using Finite Element analysis program, ANSYS. The Taguchi-based design of experiments technique was used to plan the current study. The plan included 12 box steel beams; three intact beams, and nine damaged beams (with opening) in the beams web. The numerical studies were conducted under varying the spacing between the two concentrated point loads (location of applied loads), the notch (opening) position, and the ratio between depth and width of the notch with a constant notch area. According to Taguchi analysis, factor X (location of the applied loads) was found the highest contributing parameters for the variation of the ultimate load, vertical deformation, shear stresses, and the compressive normal stresses.

Keywords Box steel beam · Structural performance · Finite element analysis · Opening parameters · Taguchi method

Introduction

Design errors, corrosion, lack of proper maintenance, sub-standard materials, fatigue damage and vehicle-caused accidental damage are considered as the major problems in the steel structures (Kim and Yoon 2010). Fatigue damage induces cracks in the tension flange of the girders and it is critical to the service life of the girders (May et al. 2016; Zhu 2016; Fisher and Roy 2015). Corrosion reduces steel sections that can cause deterioration in steel structures. Various researches investigated the influence of the corrosion and fatigue damage on the behavior of steel structures and they also presented different methods to retrofit these steel elements. In these researches, the structural steel element may be naturally deteriorated or artificially damaged. Gillespie et al. (1996) studied two full-scale I-girders. The two girders were removed from an old and deteriorated bridge and they have 9754 mm long, 610 mm deep. The flange has 229 mm wide. A uniform corrosion occurred along the length of

the specimen. The corrosion concentrated within the bottom flange and the webs of the beams were not corroded. 40% reduction of the lower flange created these deteriorations. This corrosion caused a 29% reduction in the beam stiffness. Liu et al. (2001) carried out on wide steel beams with 2438 mm span three-point bending tests. In their studied, the tension flanges of specimens were completely cut. Their results indicated that this damage causes decreasing the maximum load of the intact beam from 200 to 106 kN. Shaat (2007) and Eltaly (2016) completely cut the bottom flanges of wide beams and box beams, respectively, at mid-span to simulate a severe section loss in the steel beams. Shaat (2007) concluded that the flexural strength and stiffness of the girders was reduced by 60 and 54%, respectively. Eltaly (2016) indicated that the strength of notched beam was dropped by 34%. Tavakkolizadeh and Saadatmanesh (2001) estimated the effect of partial cutting of the tension flange using different depths of the cut (shallow and deep). These cutting simulated 80 and 40% losses in the area of the flange for the deep and shallow cutting depth, respectively. The difference between deep and shallow cuts was the ductility loss in the case of deep cut. Tavakkolizadeh and Saadatmanesh (2003) tested composite girders with the partial cutting of the tension flange to simulate 25, 50, and 100% loss of its tensile capacity. Kim and Brunell (2011) conducted an experimental program to estimate the effect

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of the notch level in the beam web at mid-span of the steel beams. Shulley et al. (1994) studied the effect of web damage of I-girders. Specimens were tested in three-point bending. The specimens were with 711 mm span. A hole with 100 mm diameter was manufactured within the shear span at mid-height of the web.

Section losses occurred also due to creating an opening in the steel beam webs for the passage of the horizontal utility ducts. Web openings could weaken the beam at the position of the opening and decrease its overall stiffness and load carrying capacity depending on the opening size, location and shape. The beams with rectangular web openings have the smaller ultimate loads than their equivalent beams with square or circular openings (Morkhade and Gupta 2015; Rodrigues et al. 2014; Chung et al. 2001). Li et al. (2015) tested continuous composite steel beams with and without openings in the web under two point loads. All the tested beams have the same details except the slab thickness and the reinforcement. Their results indicated that the stiffness and ultimate load decrease when creating openings in the steel web.

The literature revealed that a large number of investigations were done related to the artificially damaged beams and the beam with openings in steel web, these studies were done to characterize the behavior of the beams, and these studies are still being conducted. However, there are still gaps in understanding the behavior of these beams. One reason is that the beam performance may be different depending on the parameters of the notch (opening) and the load position; therefore, any conclusions are only valid for specific cases studied. Another reason is that much research has been conducted using one-factor-at-a-time approach. The amount of fluctuations in the study results reveals that the variables involved in the artificially damaged beams are dynamic in nature and beam responses are significantly related with the simultaneous variation of parameters during studies. Therefore, DOE technique has been used to make the analysis reliable and to investigate the effects of the notch parameters and the position of the load on different criteria simultaneously.

In the current research, twelve box steel beams were studied using FE analysis program, ANSYS to investigate their structural performance up to failure in terms of the maximum load and its corresponding deflection, the shear and normal stresses and the strain. Three steel box beam without opening (notch) were used and they were called control beams. These beams are valid in the position of the applied loads. In the current study, three factors at three levels were chosen as control factors. Normally, the full-factorial design would require $3 \times 3 \times 3 = 27$ runs. The run cost and effort for such design could be unrealistic and prohibitive. The Taguchi-based DOE technique was investigated to plan the present study. Nine box steel beams with notches (opening) in

the beam web were selected from 27 notched beams using Taguchi-based design technique were analyzed. Only few authors have used the Taguchi-based DOE technique in the domain of civil and/or structural engineering (Ghazy 2012; Ghazy and Abd El Hameed 2015; Kamble et al. 2016). To the best of the authors' knowledge of this work, there is no published work evaluating the artificially damaged beams or the steel beams with web openings and the effect of beam parameters on the single-performance characteristics in these beams using Taguchi-based DOE technique. Hence, it is a good idea to perform a comprehensive investigation using Taguchi-based DOE technique to analyze the effect of the damaged beam parameters for desired performance characteristics. Thus, the results can be used by the engineers who are willing to search for a suitable analysis of a damaged beam or beam with opening. Finally, necessary confirmation tests were numerically conducted to validate the results.

Experimental design details

The experimental design using Taguchi's method provides a simple, efficient, and systematic approach for the optimization of experimental designs for performance quality (Ross 1996). The traditional experimental design methods are too complex and difficult to use. Additionally, large numbers of runs have to be carried out when the number of parameters increases. Taguchi designed certain standard orthogonal arrays by which the simultaneous and independent evaluation of two or more parameters for their ability to affect the variability of particular process characteristics can be done in a minimum number of tests.

The beam parameters (control factors) chosen for the runs were: (1) ratio between width and depth of the notch (H/B), (2) The distance between the applied loads (X), and (3) The notch position (NP). Each parameter has three levels. The area of the notch (opening) was kept constant to be 3872 mm^2 . Table 1 indicates the factors and their levels. In this study, an L9 orthogonal array with three columns and nine rows was used as illustrated in Table 2. Use of a full factorial design ($3 \times 3 \times 3$) reduced a total 27 sets of runs down to 9 runs, thereby decreasing cost, time, and effort. In addition, three control beams; CB1, CB2 and CB3 were

Table 1 Beam parameters and their levels used in the experiments

Parameter	Level (1)	Level (2)	Level (3)
H/B	0.15	0.35	0.55
X (mm)	300	600	900
NP	A	B	C

Table 2 Experimental plan using L9 OA-based Taguchi method

Beam code.	H/B	X	NP
B1	0.15	300	A
B2	0.15	600	B
B3	0.15	900	C
B4	0.35	300	B
B5	0.35	600	C
B6	0.35	900	A
B7	0.55	300	C
B8	0.55	600	A
B9	0.55	900	B

studied. The three beams are intact beams and the position of the applied loads (X) is varied; 300, 600 and 900 mm.

All the studied steel beams have 1000 mm length, 50 × 50 mm box cross section and 3 mm thickness as shown in Fig. 1. The material properties of the used beams are listed in Table 3. Notch positions are indicated in Fig. 2.

FE modeling

The FE analysis program, ANSYS was used to determine the structural performances up to the failure of the specimens. Solid185 elements were selected to simulate the studied beams (refer to Eltaly 2016; ANSYS 2009; Narmashiri and Jumaat 2011). Each element is defined by 8 nodes. There are three degrees of freedom (translations in *x*, *y*, and *z* directions) at each node. Solid185 element has swelling, plasticity, creep, large strain, large deflection and stress stiffening capabilities. In the current model, geometric and material nonlinearities were both considered into account. Multi-linear Kinematic Hardening Constants approach was selected to simulate the material nonlinearity. This approach was

selected for materials that obey von Mises yield criteria. The stress–strain curve of the steel material was defined. ANSYS program depends on Newton–Raphson method for updating the model stiffness. Load–control technique was selected in the current model. In this technique, the total load is applied. During the analysis, the load is divided into small load increments using the automatic time stepping option. This option was selected to decrease load step size when the convergence occurs for the given load step. The size of load step in the case of linear range should not be defined small and it was gradually decreased as the behavior of the beam changes from linear to non-linear stage. The load increases gradually until the beam failure occurs.

Volume was used to define the studied beam in the 3D-FE model of the studied beams. Then the material and the type of element were selected as explained above. After that, the beam model was meshed with mapped meshing technique that helps in controlling the number of elements. The analysis started with a 20 mm mesh size of the elements (coarse mesh) then the model was resolved with smaller and smaller meshes (mesh refinement). In this process, mesh sizes were considered as 10, 4 and 2 mm. Their results were compared and from this comparison process, it can be indicated that 2 and 4 mm mesh sizes give acceptable results and the difference in their results is small so that the mesh size was taken as 4 mm. The FE simulation of the damaged beam is showed in Fig. 3.

Results and discussion

The performance of studied steel beams as obtained from the numerical model; peak load, normal stresses and strain (tensile and compressive), shear stresses and the maximum vertical displacement at the ultimate loads according to

Fig. 1 Intact beam details **Table 3** Material properties of the used steel

	Modulus of elasticity (Gpa)	Density (g/cm ³)	Tensile strength (Mpa)		Strain	
			Ultimate	Yield	Ultimate	Yield
Steel	200	7.8	370	250	0.0135	0.00125

Fig. 2 Notch position (NP) **Fig. 3** Numerical model

the proposed plan in different parameters are showed in Table 4. The results of the three intact beams; CB1, CB2 and CB3 in terms of the deformed shape, strain distribution, normal and shear stress distributions at the maximum loads are presented in Figs. 4, 5 and 6. This table and these

figures indicated that CB1 and CB2 fail due to bending and on the other hand the failure occurs on CB3 due to shear. The normal stresses reach the ultimate tensile strength of the steel material; 370 Mpa in CB1 and CB2. In CB3 beams, the applied load causes 360 Mpa maximum normal

Table 4 Numerical results of responses (raw data)

Beam no.	Pmax (kN)	Vertical deformation (mm)	Normal stresses (Mpa)		Shear stresses (MPa)	Strain	
			Com.	Ten.		Ten.	Com.
CB1	21.92	31.779	370	370	140	0.01897	0.0223
CB2	37.38	27.37	370	370	180	0.013	0.042
CB3	77.82	2.91	350	360	188	0.033	0.08
B1	17.93	20.2	370	250	137	0.0130	0.0037
B2	30.87	8.311	370	299	173.3	0.0049	0.0182
B3	50.4	15	360	350	200	0.0018	0.0018
B4	18.37	20.65	370	370	193.6	0.013	0.03
B5	33.46	19.5	370	360	183	0.025	0.027
B6	77.82	2	350	350	197	0.02	0.02
B7	21.19	35.75	370	370	170	0.013	0.024
B8	25.26	17.2	360	360	134	0.0097	0.014
B9	77.82	2	340	350	193	0.002	0.002

Fig. 4 Results of CB1 beam

stresses and 188 Mpa maximum shear stresses. In the three beams, the maximum stresses occur in the position of the applied loads and the surrounding area. Also this table and figures indicate that the beam deflection increases by decreasing the distance between the applied load while the maximum deflection in CB1 beams reaches at the mid-span 31.70 mm at 21.92 kN ultimate load and it reaches 27.37 mm at the mid-span at 37.38 kN maximum applied load in CB2. On the other hand, there is no any notable deflection occurred at mid-span of CB3 and a local buckling appears on the top flange under the applied load. The maximums strain (tensile and compressive) is noticed at the position of the applied load.

Shear and normal stresses, strain and vertical displacement distribution at the peak loads of the nine beams; B1 to B9 are indicated in Figs. 7, 8, 9, 10, 11, 12, 13, 14 and 15. It is clearly observed from Table 4 that B1 has the lowest peak load and B7 has the maximum lateral displacement. Also from this table and Figs. 7, 8, 9, 10, 11, 12, 13, 14 and 15, it can be concluded that B1, B2, B4, B5 and B7 reach the ultimate compressive strength of the steel. B4 and B7 reach the ultimate tensile strength of the steel (flexural failure) and on the other hand B3 reaches the steel shear strength (shear failure). Additionally, Figs. 7, 8, 9, 10, 11, 12, 13, 14 and 15 illustrate that in B1, B2, B3, B4, B5 and B8, the maximum stresses appear at the loads and the opening position and

Fig. 5 Shear and normal stresses, strain and deflection distributions of CB2 beam

Fig. 6 Deflection, shear and normal stresses and strain distributions of CB3 beam

the surrounding area and on the opposite side the maximum stresses appear at the load position and the surrounding area.

The comparisons between the studied beams and the opposite control beams are depicted in Table 4 and Fig. 16. Comparing the results of B1, B4 and B7 beams with CB1 control beam indicates that the opening (notch) in the beam web near the mid-span and with the H/B ratio = 0.15 as in B1 does not have a notable effect on the beam stiffness and has effects on the beam ductility and strength. This notch

decreases the ultimate load compared to the control beam with 18.20% and the corresponding deflection with 36.44% in respect to the CB1 control beam. Also the compression normal stress remains the maximum value as 370 Mpa and on the other hand the peak tensile normal stress and shear stress decrease from 370 and 140 Mpa in CB1 to be 250 and 137 Mpa in B1 beam, respectively. Additionally, this comparison illustrates that the opening position B (B4) decreases the structural performance of the beam. The maximum load

Fig. 7 Shear and normal stresses, strain and deflection distributions of B1

Fig. 8 Vertical deformation, shear and normal stresses, strain and distributions of B2 beam

dropped from 21.92 kN in CB1 to 18.37 kN in B4 with 16.2% reduction respect to CB1 and the maximum deflection in the beam reduces by about 35% compared with CB1. In addition, this compression shows that the occurrence the notch near the support and the load near the mid-span as in B7 beam does not give notable influence in ultimate load and normal stresses of the beam compared with CB1 but it has an effect on the strain and shear stresses. Hence, the shear stresses increases from 140 Mpa in CB1 to be 177 Mpa in B7. Creating the opening (notch) at the support increase the shear stresses in the beam and decrease the ability of the beam to carry the shear forces.

From Table 4 and Fig. 16, it can be clearly noticed that the ductility of the steel beam subjected to two applied loads with 600 mm separated distance between them (CB2) largely drops due to occurrence the web notch with $H/B = 0.15$ and with B notch position; B2 beam. The deflection (at the mid-span) at the ultimate load decreases by about 69.63% compared with CB2. Also the strength of this beam reduces by 17.42% than CB2 and it stiffens does not appreciably change. This beam likes CB2 fails because it reaches the maximum compressive strength; 370 Mpa. The tensile normal stress and shear stresses reduce from 370 and 180 Mpa in CB2 to be 299 and 173.3 Mpa in

Fig. 9 Vertical deformation, shear and normal stresses, strain and distributions of B3

Fig. 10 Vertical deformation, strain, shear and normal stresses distributions of B4

B2 beam. This is because of the occurrence of the notch under the loads. The ultimate load and its corresponding deflection of B5 beam decline by about 10.48 and 28.75%, respectively, than CB2 beam. B5 gives larger compressive and tensile strain than CB1 and it fails due to flexure as CB2. In addition, Table 4 and Fig. 16 shows that B8 (beam with $H/B = 0.55$ ratio and C position web opening) gives lower ultimate load by about 32.42% than CB2 beam. Its deflection at the ultimate load decreases by about 37.17% than CB2.

Table 4 illustrates that the structural behavior of CB3 beam in terms of the deflection, normal stresses and peak load does not affect by the occurrence of opening in the web at position B and A as in B6 and B9, respectively. It has an effect on the shear strength. These openings increase the actual shear stresses of the beam. In addition, this table shows that B3; this beam has web opening with $H/B = 0.15$ and the opening at position C collapses at 35.24% ultimate load lower than CB3 beam. Furthermore, this beam reaches the maximum shear stresses. This is because of the position

Fig. 11 Vertical deformation, strain, shear stresses and normal stresses distributions of B5

Fig. 12 Shear stresses and normal stresses, vertical deformation and strain distributions of B6 beam

of opening under the applied load and in the maximum shear zone of the beam.

Figure 16 Load–deflection curves at the mid-span of damaged beams and control beams.

In addition to the determination of desired (critical) beam parameters for each response, the response table from Taguchi method was used. In the case of the applied load, the desired beam has the lowest ultimate load. The beams have the maximum value for the other structural performances; normal stresses, shear stresses, strain and lateral displacement are the critical. Because Table 4 is orthogonal, it is possible to separate out the effect of each beam parameter on the response at different levels. The procedure is group the data by the factor level for each column in the orthogonal

array and takes the mean of them. For example, the mean of the maximum load for the factor (H/B) at 1, 2, and 3 Levels can be calculated by 1–3, 4–6, and 7–9 averaging runs, respectively.

The mean of any response for each level of the other process parameters can be calculated in a similar manner. The results for peak load were listed in Table 5. The difference between the maximum and the minimum value (delta) of the data for the peak load are listed in Table 5. The most effective controllable factor was the maximum of these values. On the other hand, the significance of the role that every controllable factor plays over the performance characteristic can be obtained by examining these values. The effect of each control factor can be determined from the value of

Fig. 13 Vertical deformation, strain, shear and normal stresses distributions of B7

Fig. 14 Vertical deformation, strain, stresses shear and normal stresses distributions of B8

delta, based on which Table 5 shows, factor X has the largest delta and thus has the most significant influence (Rank 1) on the peak load. From the analysis of Table 5, it was observed that the percentage contribution of the control factors affecting the peak load is X (74.3%), H/B (15%), and NP (10.7%).

Figure 17 shows the main effects plot of peak load. From this figure, it is observed that the variation of parameter X has a critical role on peak load, which increases with parameter X . It is revealed from the same figure that the H/B factor has the same trend of factor NP . The critical value of factor (H/B) is at 0.35 mm. From the same figure, it is obvious that

factor NP has the weakest effect on peak load and its critical position of the notch is at B.

From Table 5 and Fig. 17, the beam parameter levels for minimum peak load (critical beam) can be given as for $H/B = 0.15$, $X = 300$ mm, and NP at C. Because these combination parameters are selected from the response table (Table 5) according to Taguchi analysis, and these combination parameters are not found in the orthogonal array (Table 3), the confirmation test analysis for this beam is processed. It is a good idea to plan on running an additional sample at this condition. The expected result is considered to

Fig. 15 Vertical deformation, strain, shear and normal stresses distributions of B9

be confirmed when the mean of a number of samples studied at the selected condition falls close to it.

The result of confirmation test analysis is compared with the initial condition of design operating parameters. It is obvious from Table 5, that Beam No 1 (B1) has the lowest peak load value (17.93 kN) compared to the other beams. Therefore, it can be concluded that Beam No.1 possesses initial setting parameters. Table 5 shows the compared results of the desired beam parameters ($H/B = 0.15$, $X = 300$ mm, and NP at C) and initial design parameters ($H/B = 0.15$, $X = 300$ mm, and NP at A). For the single performance characteristic, the peak load is reduced from 17.93 to 14.14 kN. The predicted (calculated) peak load using the optimal level of desired (critical) beam parameters can be calculated from the following Eq. 1 (Ross 1996):

$$\eta_{\text{pred}} = \eta_m + \sum_{i=1}^n (\eta_i + \eta_m) \quad (1)$$

where η_m is the total mean of the raw data, $\sum_{i=1}^n (\eta_i + \eta_m)$ is the all improvement (contribution) from all; η_i is the mean of the raw data at the optimal level; and n is the number of the beam parameters that significantly affects the performance characteristic.

Table 5 indicates the comparison of predicted values with that of actual using the critical beam parameters and the initial setting parameters (B1) of peak load, a good agreement between the actual and predicted results was obtained. For simplicity and avoiding lengthy statement the responses; namely normal stresses and strain (tensile and compressive), shear stresses and deflection at peak loads can be analyzed in a similar manner using Taguchi method. Tables 6, 7 and 8 indicate the comparison of predicted values with that of

actual using the critical beam parameters and the initial setting parameters for different responses of the beams, a good agreement between the actual and predicted results were obtained.

The effect of each control factor can be determined from the value of delta and the percentage contribution, based on which Tables 5, 6, 7 and 8 show that factor X (location of the applied loads) has the largest delta and the percentage contribution, and thus has the most significant influence (Rank 1) on the peak load, vertical deformation, shear stresses, and compressive normal stresses. From the same Tables, it was observed that factor H/B (ratio between width and depth of the notch) is the most significant control factor affecting the compressive strain, tensile strain, and compressive normal stresses. From the same tables, it is obvious that factor NP (position of the notch) has the weakest effect on the peak load, compressive strain, tensile strain, shear stresses, and tensile normal stresses.

Conclusions

In this paper, the parameters of the artificially web damaged (opening) beam were determined from single-performance characteristics (peak load, normal stresses and strain (tensile and compressive), shear stresses and deflection at peak loads). An application of Taguchi method has been reported. Based on the numerical results achieved in the presented research study, the following conclusions can be drawn:

- (1) B1 has the lowest peak load and B7 has the maximum lateral displacement from the nine notched beams.

Fig. 16 Load-deflection curves at the mid-span of damaged beams and control beams

Table 5 Response table for means (raw data) and results of confirmatory experiments of peak load

Level	H/B	X	NP
1	33.07	19.16	40.34
2	43.22	29.86	42.35
3	41.42	68.68	35.02
Delta	10.15	49.52	7.34
Rank	2	1	3
Contribution%	0.15	0.735	0.18
Parameters of critical beam	0.15	300	C
Predicted value of critical beam (TAGUCHI) Eq. 1	8.77556 kN		
Numerical value of critical beam (ANSYS)	14.14 kN		
Initial setting parameters (Table 4—Beam No.1)	17.93 kN

Fig. 17 The main effects plot of peak load **Table 6** Response table for raw data and results of confirmatory experiments of lateral displacement and shear stress

Level	Lateral displacement			Shear		
	H/B	X	NP	H/B	X	NP
1	14.50	25.53	13.13	170.1	166.9	156.0
2	14.05	15.00	10.32	191.2	163.4	186.6
3	18.32	6.33	23.42	165.7	196.7	184.3
Delta	4.267	19.20	13.1	25.5	33.2	30.6
Rank	3	1	2	3	1	2
Contribution	0.116	0.525	0.358	0.285	0.371	0.343
Parameters of desired beam	0.55	300	C	0.15	900	B
Predicted value of desired beam (Taguchi) Eq. 1	36.0198 mm			202.089 Mpa		
Numerical value of desired beam (ANSYS)	35.75 mm			200 Mpa		
Initial setting parameters (Table 4)	35.75 mm			200		

Table 7 Response table for raw data and results of confirmatory experiments of normal stresses

Level	Normal stresses					
	Compression			Tension		
	H/B	X	NP	H/B	X	NP
1	366.7	370.0	360.0	299.7	330.0	320.0
2	363.3	366.7	360.0	360	339.7	339.7
3	356.7	350.0	366.7	360	350.0	360.0
Delta	10.0	20.0	6.7	60.3	20.0	40.0
Rank	2	1	3	1	3	2
Contribution	0.274	0.549	0.176	0.5	0.166	0.33
Parameters of desired beam	0.15	300	C	0.35	900	C
Predicted value of desired beam (Taguchi) Eq. 1	378.889 Mpa			390.222 Mpa		
Numerical value of desired beam (ANSYS)	370 Mpa			370 Mpa		
Initial setting parameters (Table 4)	370 Mpa			370 Mpa

Table 8 Response table for raw data and results of confirmatory experiments for strain

Level	Strain					
	Compression			Tension		
	<i>H/B</i>	<i>X</i>	NP	<i>H/B</i>	<i>X</i>	NP
1	0.0079	0.0192	0.0126	0.0066	0.0130	0.01423
2	0.0257	0.0197	0.0167	0.0193	0.0132	0.00663
3	0.0133	0.0079	0.0176	0.0082	0.0079	0.01327
Delta	0.0178	0.0118	0.0050	0.0128	0.0053	0.0076
Rank	1	2	3	1	3	2
Contribution	0.513	0.341	0.145	0.498	0.205	0.296
Parameters of desired beam	0.35	600	C	0.35	600	A
Predicted value of desired beam (Taguchi) Eq. 1	0.0317333			0.0240111		
Numerical value of desired beam (ANSYS)	0.025			0.032		
Initial setting parameters (Table 4)	0.03			0.025		

- (2) B1, B2, B4, B5 and B7 reach the ultimate compressive strength of the steel. B4 and B7 reach the ultimate tensile strength of the steel (bending failure) and on the other hand, B3 reaches the steel shear strength (shear failure).
- (3) The maximum stresses appear at the applied loads, at the opening position and at their surrounding area in B1, B2, B3, B4, B5 and B8 beams and on the opposite side the maximum stresses appear at the applied load position and the surrounding area in B6, B7 and B9.
- (4) The opening (notch) in the beam web near the mid-span and with the H/B ratio = 0.15 as in B1 does not have a notable effect on the beam stiffness and has effects on the beam ductility and strength compared with CB1 beam.
- (5) The ductility of the steel beam subjected to two applied loads with 600 mm separated distance between them (CB2) largely drops due to occurrence the web notch with $H/B = 0.15$ and with B notch position; B2 beam. The deflection (at the mid-span) at the ultimate load decreases by about 69.63% compared with CB2. Also the strength of this beam reduces by 17.42% than CB2.
- (6) The structural performance of CB3 beam in terms of the peak load, deflection and normal stresses does not affect by the occurrence of opening in the web at position A and B as in B6 and B9, respectively.
- (7) The position of the opening under the applied load and in the maximum shear zone of the beam (B3) decreases the ultimate load by about 35.24% than CB3 beam.
- (8) Based on Taguchi analysis, factor X (location of the applied loads) was found to be the highest contributing parameters for variation of the peak load, vertical deformation, shear stresses, and compressive normal stresses.
- (9) It has been found that factor H/B (ratio between width and depth of the notch) is the most significant control factor affecting the compression strain, tensile strain, and compressive normal stresses.
- (10) Taguchi analysis revealed that factor NP (position of the notch) has the weakest effect on peak load, compression strain, tensile strain, shear stresses, and tensile normal stresses.
- (11) Results have been confirmed on the desired beam setting parameters for single response and the errors in numerical values with respect to the predicted values are within the acceptable range of error.
- (12) It can be concluded that the Taguchi method is most ideal and suitable for the parametric analysis of the artificially damaged beam when using the single-performance characteristics.

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