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Study of Darwin guidelines for non-compact and slender steel girders with web openings

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Abstract: *Steel beams with web openings are used to provide the utilities of the structure within the constructional depth to give a good architectural emphasis. The provision of these web openings has a significant effect on the stress distribution and deformation characteristics. One of the famous guidelines used to determine the strength of steel and composite beams having web openings with or without reinforcement was Darwin's guidelines which are considered as a reference in the American code. According to Darwin conditions, these guidelines are limited to use for beams with compact webs only. But as is well-known, non-compact and slender sections are widely used in design of the steel structures because they are more economic. Therefore, the objective of this paper is to study the accuracy of using Darwin guidelines in cases of steel beams with non-compact or slender sections. An analytical investigation has been developed by using nonlinear finite element modelling technique. ANSYS program is used considering both geometric and material nonlinearities. Finite element models results are verified with the results of experimental tests and numerical analyses found in the literature. The results show that Darwin guidelines can be used for some cases of perforated beams with non-compact and slender webs when the openings are located at high shear zone as well as at high moment. They cannot be used when the openings are located at the moment-shear combination zones. Therefore, it must be amended to be used for these cases.*

Keywords: *web opening; perforated steel girder; Darwin guidelines; Finite element modelling; non-compact sections and slender steel web.*

I. Introduction

Steel beams with web openings combine beauty, versatility, economy in steel design. In modern buildings, openings are frequently required to be provided in structural members so that building services may be incorporated into structural zones for simplified layout and installation. Moreover, the overall depth of the construction zone may be reduced accordingly, and this is beneficial for multi-story buildings with large headroom requirements. Unfortunately, most of perforated steel beams have high stress concentrations at the corners of the openings in addition to the decrease in the beam strength and increase in its deformations.

In the 1960s, 1970s, and 1980s, studies on different web opening configurations were completed in different countries, including square, rectangular, circular, concentric, and eccentric openings in both non-composite and composite steel beams. Congdon and Redwood [1] estimated the strength of compact web beams which have single reinforced rectangular openings by using experimental tests and assuming perfectly plastic behavior. Cooper and Snell [2] conducted an experimental investigation on simply supported beams to study the accuracy of the vierendeel method in calculating normal and shear stresses at the perforated sections. Lupien and Redwood [3] used experimental tests to estimate the strength of simply supported beams which have rectangular web openings at mid of their depths. Redwood and Cho [4] investigated the behavior of steel and composite beams with web openings and developed a general method to predict their ultimate strength and related it to the available design aids. Prakash, et al. [5] carried out a finite element analysis using ANSYS software to study steel and composite compact beams with unreinforced and reinforced centrally single rectangular web opening. They observed that the web opening in low shear and high moment region tend to perform better than web opening in the high shear region. Akwasi and Hsiao [6] used finite element analysis to study the behavior and variations of stresses for compact perforated steel beams due to the variations in their cross section dimensions. Abdul Gabar [7] studied the structural behavior of perforated compact steel plate girders under shear. Formulas were presented to predict the ultimate shear load of perforated steel girders with large openings by using a nonlinear finite element analysis. Darehshouri, et al. [8] developed an analytical method to determine the ultimate shear capacity of composite plate girders containing web openings. They accounted the contributions to the shear strength of the girder by tension field action in the plate girder web panel and shear failure of concrete slab. In the late 1980s, several important researches focused on this subject, such as: Darwin and Donahey [9], Darwin and Lucas [10] and Darwin [11]. They demonstrated that it is possible to produce a unified procedure embodying the different cases that are frequently used in steel building structures.

Darwin [11] prepared a guide for the design of steel and composite beams with web openings due to the recommendations of the committee of research of the American Institute of Steel Construction. This is part of a series of publications on special topics related to fabricated-structural steel beams. Its purpose is to serve as a supplemental reference to the AISC manual of Steel Construction to assist practicing engineers engaged in building design [12]. This design guide presents a unified approach to the design of structural steel members with reinforced or unreinforced web openings but this guide is limited to compact sections only. Also the most of researches and codes concentrated on perforated beams with compact sections. Most of steel beams are fabricated as non-compact or slender sections to minimize the cost of construction. This makes the necessity to investigate this type of steel beams with web openings to estimate their strength with or without reinforcement.

The objective of this research is to study the accuracy of using Darwin guidelines for different cases of perforated beams with non-compact and slender webs when the openings have square and rectangular shapes by comparing the value of maximum load capacity for each beam which is calculated numerically according to Darwin's guidelines with that obtained analytically from finite element analysis by ANSYS [13]. There are different parameters considered such as opening height-to-beam depth ratio, opening width–to-height ratio, position of opening along the beam length, thickness of web and reinforcement techniques around the web opening.

II. Methodology

ANSYS [13] Workbench provides an excellent platform for analysis of various structural systems. It easily modelled steel beams and steel beams with web openings using the geometry modeller. Present study focuses on the calculation of load capacity for non-compact and slender steel beams with single web opening at various positions along beam span by using ANSYS software. Based on the results of ANSYS, the results obtained according to Darwin guidelines are compared. Then the accuracy of using Darwin guidelines for this type of beams are checked.

III. Darwin's Guidelines

Darwin's guidelines [11] represent the guide reference to the AISC manual of Steel Construction [12]. This design guide presents a unified approach to the design of structural steel members with reinforced or unreinforced web openings. These guides are limited to compact sections only. They are dependent on the interaction between the moment and shear. The moment capacity of the perforated beam will be reduced at the opening due to the reduction in the contribution of web to the moment capacity. Darwin's guidelines give relations between the actual bending and shear capacities and the corresponding maximum nominal capacities at opening centreline as detailed in Eq. (1). The value of the maximum capacity of uniformly distributed load Wu for the perforated beam at opening centreline can be calculated according to Darwin's guidelines [11] as follows:

$$\left(\frac{M_u}{\varnothing M_m}\right)^3 + \left(\frac{V_u}{\varnothing V_m}\right)^3 \le R^3,\ R=1.0 \qquad \text{(Eq. 1)}$$

Where:

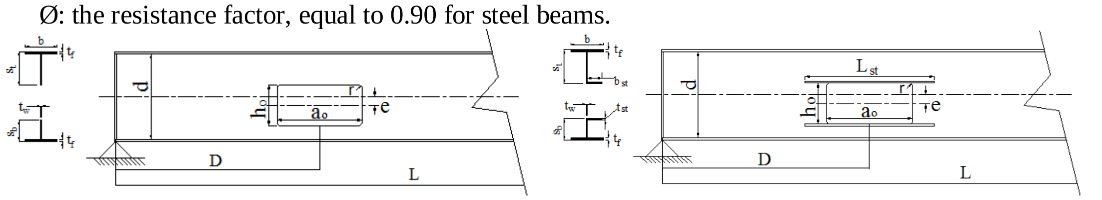
M_u: the factored bending moment at opening centreline

V_u: the factored shear at opening centreline

M_m: the maximum nominal bending capacity at the location of opening centreline under pure bending; it occurs when V_u= 0.

V_m: the maximum nominal shear capacity at the location of an opening centreline under pure shear; it occurs when M_u= 0.

Ø: the resistance factor, equal to 0.90 for steel beams.



a- un-reinforced opening b- reinforced opening

Fig. 1. Dimensions of un-reinforced and reinforced opening in steel beams according to Darwin guidelines [11]

The actual moment; M_u and shear; V_u at opening centreline at any position along the beam span can be expressed as a function in the unknown uniform failure load W_u as detailed in Eq. 2 and Eq. 3.

$$M_u\ (D) = \frac{W_u}{2}\left[LD - \frac{D^2}{2}\right] \qquad \text{(Eq. 2)}$$

$$V_u\ (\mathrm{D}) = W_u\left[\frac{L}{2} - D\right] \qquad \text{(Eq. 3)}$$

Where:
D: the distance between centreline of a supposed opening and beam support.
L: the length of beam span.
W_u: uniformly distributed load on the simply supported beam.

The capacities of nominal bending (M_m) and nominal shear (V_m) at the location of web opening depend on many factors such as: opening shape and dimensions, the plastic flexural (M_p) and shear (V_p) strengths of an unperforated steel beam. Darwin [11] gave a numerical method to determine the values of M_m and V_m by knowing M_p and V_p as follows:

- For unreinforced opening

$$M_m = M_p\left[1 - \frac{(\frac{h_0^2\, t_w}{4})}{Z}\right] \qquad ;\ \text{where } M_p = F_y\, Z$$

$$\therefore M_m = F_y\left[Z - (\frac{h_0^2\, t_w}{4})\right]$$

$$V_m = V_{mb} + V_{mt} \leq 2/3\ V_p$$

$$V_{mb} = V_{pb}\,\alpha_{vb} \quad \text{and} \quad V_{mt} = V_{pt}\,\alpha_{vt}$$

Where:

$$V_p = \frac{F_y\, d\, t_w}{\sqrt{3}}\ ,\ V_{pb} = \frac{F_y\, S_b\, t_w}{\sqrt{3}} \text{ and } V_{pt} = \frac{F_y\, S_t\, t_w}{\sqrt{3}}$$

$$\alpha_{Vb} = \frac{\sqrt{6}}{\frac{a_0}{S_b} + \sqrt{3}} \leq 1.0 \text{ and } \alpha_{Vt} = \frac{\sqrt{6}}{\frac{a_0}{S_t} + \sqrt{3}} \leq 1.0$$

V_{mt}, V_{mb}: are the maximum shear capacities of the top and bottom tees respectively.
V_{pt}, V_{pb}: are the plastic shear capacities of the top and bottom tees respectively.
d, t_w: are the web depth and thickness respectively.
h_0, a_0: are the opening depth and width respectively.
S_b, S_t: are the depths of bottom and top tees respectively as shown in Figures. 1 and 8
α_{Vb},α_{Vt}: are the ratios of maximum nominal shear strengths to plastic shear stresses of bottom and top tees respectively.
Z: plastic section modulus
F_y: yield strength of steel

- For reinforced opening:

$$M_m = M_p\left[1 - \frac{(\frac{h_0^2\, t_w}{4} - h_0 A_r)}{Z}\right] \leq M_p$$

$$\therefore M_m = F_y\left[Z - (\frac{h_0^2\, t_w}{4} - h_0 A_r)\right] \leq M_p$$

$$V_m = V_{mb} + V_{mt} \leq 2/3\ V_p$$

$$V_{mb} = V_{pb}\,\alpha_{vb} \quad \text{and} \quad V_{mt} = V_{pt}\,\alpha_{vt}$$

Where: $$\alpha_{Vb} = \frac{\sqrt{6} + \mu_b}{\frac{a_0}{S_b} + \sqrt{3}} \leq 1.0 \text{ and } \alpha_{Vt} = \frac{\sqrt{6} + \mu_t}{\frac{a_0}{S_t} + \sqrt{3}} \leq 1.0$$

A_r: Cross-sectional area of reinforcement along top or bottom edge of opening= $b_{st}\, t_{st}$
P_r: force in reinforcement along edge of opening = $F_y\, A_r \leq \frac{Fy\ tw\ ao}{2\sqrt{3}}$
d_r: distance from outside edge of flange to centroid of reinforcement.

μ_b, μ_t : Dimensionless ratios of bottom and top tees respectively

$$\mu_b = \frac{P_r\, d_r}{V_{pb}\, S_b} \quad \text{and} \quad \mu_t = \frac{P_r\, d_r}{V_{pt}\, S_t}$$

The value of W_u can be calculated according to Darwin's guidelines by substituting from equations Eq. 2 and Eq. 3 in equation Eq. 1.

IV. Finite Element Analysis

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. [14] In this paper, a three dimensional finite element model is developed to stimulate the behavior of steel beams with web openings having an I-shaped cross section. Various finite element models are developed for determining the load capacity for steel beam with various web thicknesses. Different dimensions of web openings are considered at various positions along the beam span. Useful results have been obtained. Four-node shell element SHELL181 is used to model all the steel elements. This includes the top and bottom flanges, web, and steel reinforcements. The generation of element is done taking into consideration the opening position, as the mesh is fine near the opening and denser away from it. So, the mesh size is varied to ensure consistent behavior of the model. The compression flange was provided by lateral restraint to prevent lateral torsional buckling. Figure 2 shows a typical finite element mesh of perforated steel beam. The stress–strain relationship for the steel material was taken as elastically–perfect plastic with a modulus of elasticity (E) equal to 2.1E+08 kN/m² and Poisson's ratio of 0.3.

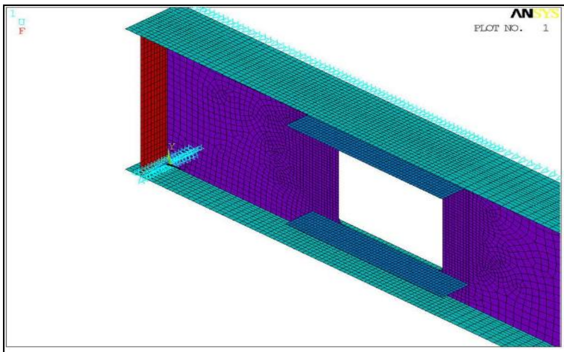


Fig. 2. typical finite element mesh of perforated steel beam by authors

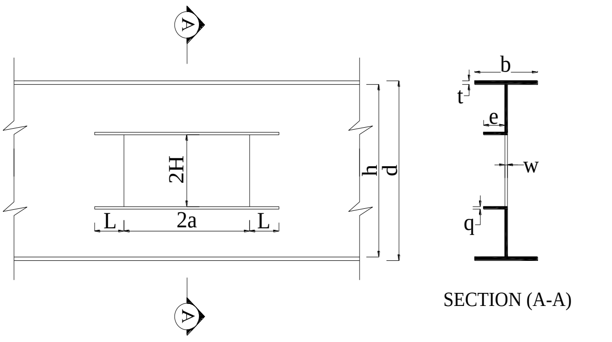


Fig. 3. Detail of beams used in verification by Lupien and Redwood [3].

Table 1: Cross section dimensions of beams used in verification by Lupien and Redwood [3]

Beam	d (in)	b (in)	t (in)	w (in)	h (in)	q (in)	e (in)	2a (in)	2H (in)	L (in)
RL2	20.56	6.88	0.392	0.253	19.78	0.368	2.281	33.75	13.50	4.44
RL3	20.63	7.06	0.377	0.252	19.88	0.368	2.281	22.50	9.00	4.00

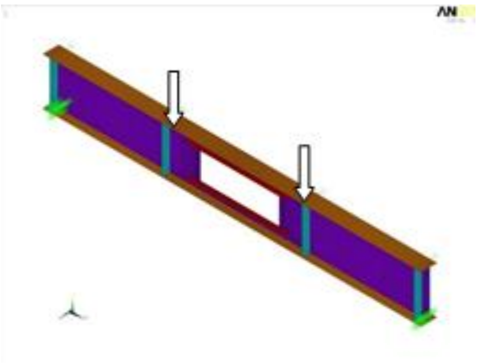
Table 2: Material properties of beams which were considered by Lupien and Redwood [3]

Beam	Yield stress f_y (kip/in²)		
	Flanges	Web	Reinforcement
RL2	54.17	58.67	43.31
RL3	53.23	58.26	43.78

V. Verification Of The Finite Element Model

The reliability of the proposed finite element models are checked by verifying their results with the previous experimental results which were performed by Lupien and Redwood [3]. They tested two simply supported steel beams RL2 and RL3 with mid depth rectangular web openings as shown in Figure 3. The openings were reinforced horizontally from one side of beam web, above and below the opening. The dimensions and material properties of the tested beams are presented in Table 1 and Table 2 respectively. The center of opening was localized at the middle and the first one third of beam span for beams RL2 and RL3 respectively. The applied concentrated loads acted at the end of one third and the end of the last third of beam span for beam RL2, while it affected at the mid of beam span for beam RL3. The two tested beams were modelled by using FEA as shown in Figure 4.

To confirm the accuracy of finite element model, the analytical results which are carried out by Prakash, et al. [5] on simply supported perforated steel beams are used in the verification. They studied the effect of rectangular web opening with different aspect ratios on yield load ratio and deflection due to distributed load equal 100 kN/m2 (from top flange area). Different cases of web opening with and without reinforcement are investigated. The value of the yield stress considered for both I-section as well as for strengthening plate is 250 N/mm.


a) Beam RL2

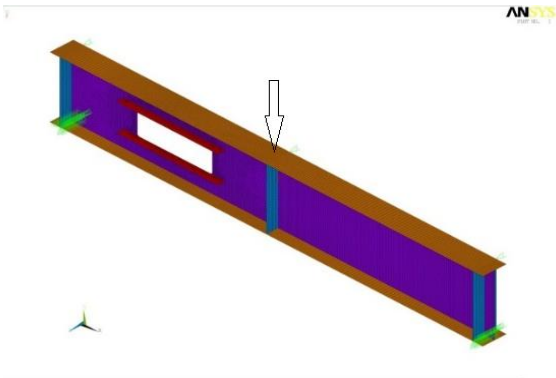

b) Beam RL3

Fig. 4. Typical finite element model by authors for beams used in verification from Lupien and Redwood [3]

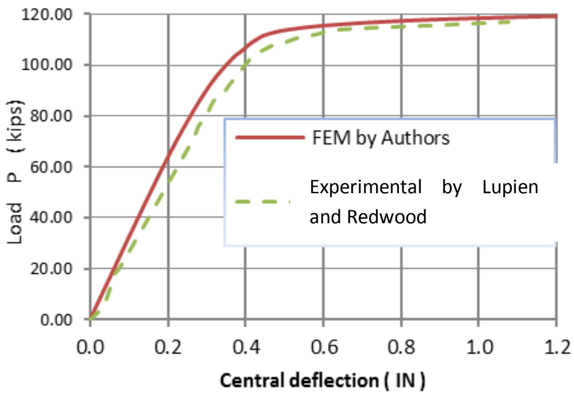


Fig. 5 (Load- deflection) curve for beam RL2

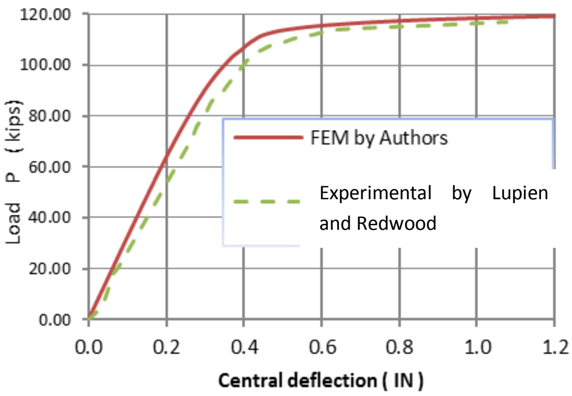
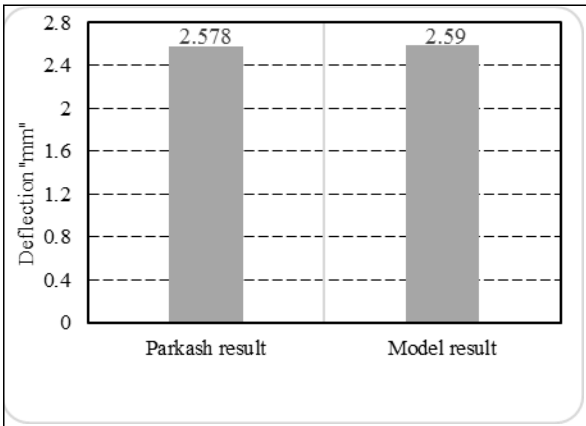
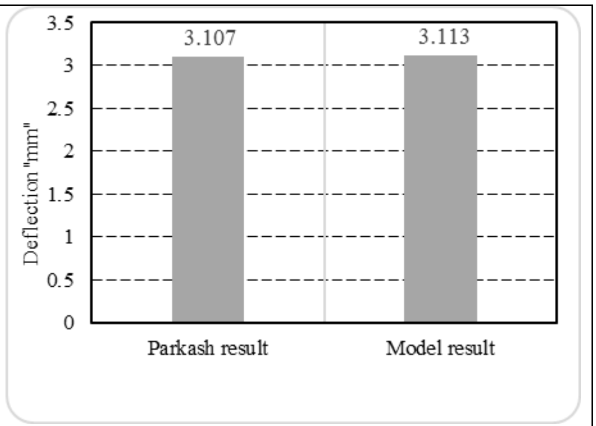


Fig. 6 (Load- deflection) curve for beam RL3

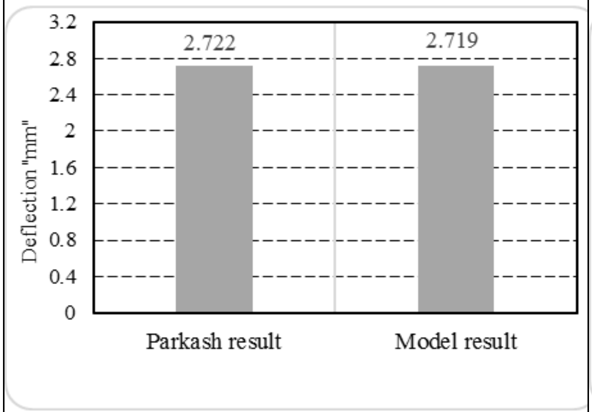
Figures 5 and 6 show the comparisons between the load-deflection curves resulted from the FEA by the authors and the experimental tests by Lupien and Redwood [3]. Figure 7 show the comparisons between deflection values resulted from the FEA by the authors and those by Prakash, et al. [5]. It can be observed from the figures that the results obtained by the proposed finite element models by the authors have a fair agreement with those obtained experimentally by Lupien and Redwood [3] and analytically by Prakash, et al. [7] with tolerances less than 2% which validates the effectiveness of the adopted structural model.



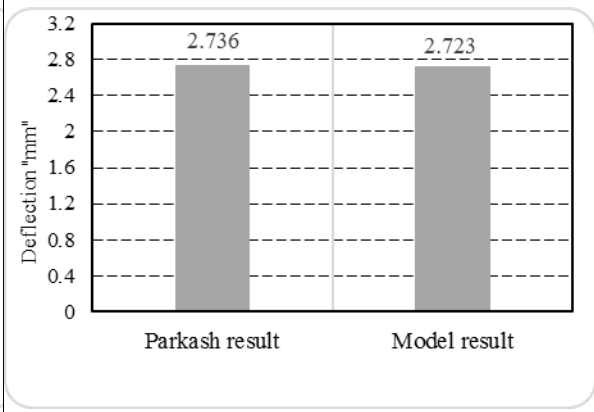
a-Beam without opening



b-Beam having unreinforced opening with height = 0.62 of beam depth and opening width twice opening height



c-Beam having reinforced opening with height = 0.50 of beam depth and opening width twice opening height



d- Beam having reinforced opening with height = 0.50 of beam depth and opening width twice opening height

Fig. 7 Deflection for beam with opening position to span ratio at 0.10

VI. Parametric Study

An extensive parametric study using the finite element model described earlier is conducted. The study is performed by deducing the uniform failure load for a simple supported perforated steel beam which is shown in Fig. 8 with dimensions and properties as illustrated in table 4. It was used as a base in the form of twenty models (G1 to G20) with different opening dimensions and positions as is illustrated from Tables from 5 to 8. The effect of many parameters on the capacity of the perforated beams are investigated such as the opening shape, the opening height, the opening width, the position of the opening along the beam span and the compactness ratio of beam web. The opening shapes were considered as square with aspect ratio $a_o/h_o = 1.0$, and as rectangular with length twice its height ($a_o/h_o = 2.0$). The opening height (h_o) is taken as 0.50, and 0.70 from the beam depth (d). Likewise, the opening width (a_o) is considered as once, and twice the opening height (ho). Five locations of the opening were considered. The distance (D) of the opening center from the left support was taken equal to 10%, 20%, 30%, 40%, and 50% of beam span (L). The effect of web compactness is investigated; the web depth was considered equal to 750mm for all models while its thickness varied from 5 to 8 mm. where the web is slender when its thickness was taken equal to 5 or 6 mm. When the web is non-compact, its thickness was taken equal to 7 or 8 mm. The study is conducted for all models for the cases when the openings are unreinforced and reinforced with extended horizontal stiffener above and below the opening from one side only of the web.

Some assumptions were considered in the modelling such as, no lateral buckling for beams; where all models were fully laterally restrained. Also, no stress concentration around supports, where double bearing stiffener plates with dimensions 750 x 90 x 12 mm were provided at each support. One support was considered as a hinged support while the other support was simulated as a roller support. Finally, all openings were centered vertically with respect to the webs of beams.

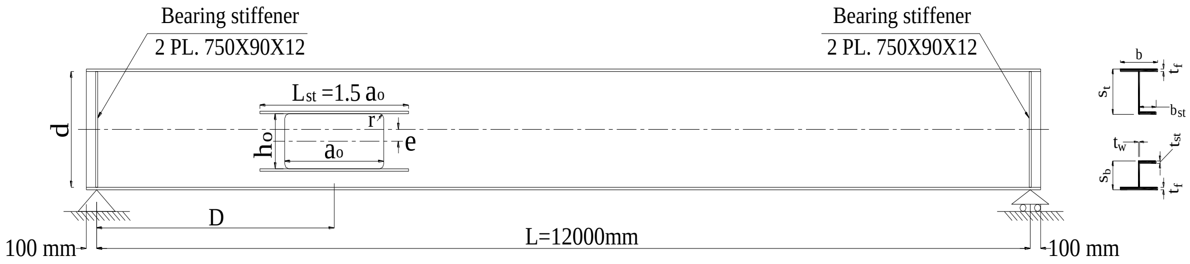


Fig. 8 Layout configuration of the studied beam

Table 4: Section properties of the studied beam

d (mm)	b (mm)	t_w (mm)	t_f (m)	L (mm)	r (mm)	b_{st} (mm)	t_{st} (mm)	F_y (N/mm²)
750	200	5,6,7, and 8	12	12000	20	80	10	235

Tables from 5 to 8: Summary of different parameters considered in the study of beams with single opening

Table 5 : Beams with square opening and h_o/d =0.50

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L}$%
G1	1	10
G2		20
G3		30
G4		40
G5		50

Table 6 : Beams with rectangular opening and h_o/d =0.50

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L}$%
G6	2	10
G7		20
G8		30
G9		40
G10		50

Table 7 : Beams with square opening and h_o/d =0.70

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L}$%
G11	1	10
G12		20
G13		30
G14		40
G15		50

Table 8 : Beams with rectangular opening and h_o/d =0.70

Beam No.	$\frac{h_o}{d}$	$\frac{D}{L}$%
G16	2	10
G17		20
G18		30
G19		40
G20		50

VII. Results And Discussions

The values of the uniform failure loads (W_u) at the opening for each beam are calculated numerically according to Darwin's guidelines and analytically by using FEA. The comparison of the two methods is done on the bases that the web openings in the two cases are without and with reinforcement. In order to observe the compactness effect for all beams from G1 to G20, the value of the failure load W_u for different compactness ratios for each beam and for different opening positions according to FEA as well as Darwin's guidelines is obtained and plotted in chart forms as shown in Figures 9 to 24.

The accuracy of using Darwin's guidelines in the calculation of the load capacity for perforated beams with non-compact and slender webs is studied by using the percentage variation between the results of the uniform failure loads W_u which are calculated according to Darwin's guidelines and FEA methods. The percentage of variation is calculated from the following equation:

$$\%\text{variation} = \frac{W_u\ (\text{FEA}) - W_u\ (\text{Darwin})}{W_u\ (\text{Darwin})}$$

If the percentage of variation has a positive value, it means that Darwin's guidelines give value of beam failure load W_u less than its accurate value which is obtained from the F.E.A. Therefore, in this case Darwin's guidelines can be used with some losses in the beam capacity. On the contrary, the negative value of the percentage of variation means that Darwin's guidelines give value of W_u higher than that resulted from F.E.A. Then, Darwin's guidelines can be conservatively used when the negative value of the variation percentage is small while it cannot be used for cases of high negative values.

The percentage of variation for each beam of the twenty beams (G1 to G20) is calculated while considering the web thickness of each beam varying from 5 to 8mm. Figures 13, 14, 19 and 20 give good information about the relation between the web thickness of each beam and the corresponding variation percentage. These Figures illustrate that the percentage variation between the results of Darwin and FEA is different according to the position of the opening with respect to the beam span (D/L), the ratio between opening and web depths (h_0/d), the opening length depth ratio (a_0/h_0) and the web thickness. It is mainly dependent on the ratio between opening and web depths (h_0/d) and the position of the opening with respect to the beam span (D/L). The Figures show that the percentage variation changes depend on the presence of the web opening through three different zones of the beam span. These zones are: high shear zone at D/L=0.1, a high moment zone at D/L=0.4-0.5 and combination zone between shear and moment at D/L=0.2 – 0.3.

7-1) Beams having web opening with (h_o/d = 0.50):

This type of beams has been studied through models from G1 to G5 for square openings and from G6 to G10 for rectangular openings as detailed before in Tables 5 and 6 respectively. Figures 9 to 12 show the differences between the values of the uniform failure loads W_u according to Darwin and FEA for models from G1 to G10 with un-reinforced openings and different web thicknesses. Figures 21 and 22 show the differences between the results of the same models but with reinforced openings. It is found that the results of all beams vary depending on the opening location with respect to the three zones which are mentioned before as follows:

- **Beams with opening at high shear zone (D/L=0.1)**

This category of beams has been studied through models G1 and G6 for square and rectangular openings respectively. It is found that the values of Wu which are calculated according to Darwin's guidelines are higher than those resulting from FEA for these beams with any web thickness as shown in Figures 9 to 12. Figures 13 and 14 show the rate of variation between the results of Darwin and FEA for these beams with different web thicknesses. It is observed that percentage of variation for the same beam increases due to the decrease in its web thickness. When, the variation percentage for model G1 equals 5.33% at t_w=8mm and increases gradually to reach 13.65% when t_w=5mm. The percentage of variation is higher in case of square opening than that in case of a rectangular opening for the same web thickness where, it equals 13.65% and 9.85% for models G1 and G6 respectively with t_w=5mm. The positive values of the percentages of variations mean that Darwin's guidelines give values of W_u less than that obtained from F.E.A for these beams. Figures 21 and 22 explained the same thing for models G1 and G6 with reinforced openings.

From the above it is clear that for non-compact and slender beams with square and rectangular openings having heights equal to 0.5 the beams depth (h_o/d=0.5), Darwin's guidelines give conservative values of W_u when the openings are located at the high shear zone (D/L=0.1) for un-reinforced or reinforced openings.

- **Beams with opening at high moment zone (D/L=0.4-0.5)**

This category of beams has been studied through models G4 and G5 for square openings and models G9 and G10 for rectangular openings with a_0/h_0=2. It is clear from Figures 9 to 12 that the results of Darwin and FEA are close for all beams with different web thicknesses with unreinforced and reinforced openings as is also clear from Figures 21 and 22.

Figures 13 and 14 indicate that the relation between the percentage variation of W_u for each beam with same web thickness has small negative values ranging from -1.82% to -4.19%. This means that, Darwin's guidelines give values of W_u for this type of beams higher than those obtained from F.E.A with small differences and the percentage of variation is not affected by the difference in the thicknesses of beams webs. The compactness of web for this type of beams has small effect on its failure load capacity W_u, which is governed mainly by the moment capacity of the perforated beam section where the shear at the section of opening equals zero and then the effect of web buckling and vierendeel mechanism are ignored.

Thus, Darwin's guidelines can be used for non-compact and slender steel beams which have un-reinforced or reinforced opening with height-to-beam depth ratio (h_o/d) equal to 0.50 and opening width to height ratio (a_o/h_o) up to 2.0 when the opening is located at high moment zone at D/L ratio=0.4 and 0.5.

- **Beams with opening at moment-shear combination zone (D/L=0.2 – 0.3)**

This category of beams has been studied through models G2 and G3 for square openings and models G7 and G8 for rectangular openings with a_0/h_0=2. The results of Darwin and FEA are shown in Figures 9 to 12. It is observed that there are clear differences between the results of the two methods for each beam of these beams. Figures 13 and 14 indicate that the percentage variation between the results of Darwin and FEA increases due to the increase in the beam web thickness while for beam G2 the percentage of variation equals 0.89% and -7.16% for t_w=5mm and 8mm respectively. The same can be observed from Figures 21 and 22 for the same beams with reinforced opening, where the results of the two methods have clear differences also. The percentage of variation for these beams have high negative values, where it equals -7.16 and -12.8 for G3 and G8 respectively for t_w=8mm. This is means that, Darwin guidelines give values of W_u for this type of beams higher than those obtained from F.E.A with high differences. It is illustrated that Darwin's guidelines cannot be used for non-compact and slender steel beams which have un-reinforced or reinforced openings with height-to-beam depth ratio (h_o/d) equal to 0.50 and located at the zone of combination between moment and shear (D/L=0.2 – 0.3) especially for rectangular openings with aspect ratio (a_o/h_o) up to 2.0.

7-2) Beams having web opening with (h_o/d = 0.70):

This type of beams have been studied through models from G11 to G15 for square openings and from G16 to G20 for rectangular openings as detailed before in Tables 7 and 8 respectively. Figures 15 to 18 show the differences between the results of the uniform failure loads W_u according to Darwin and FEA for models from G11 to G20 with un-reinforced openings for different web thicknesses. Also, Figures 23 and 24 show the same results, but for models having reinforced openings.

- **Beams with opening at high shear zone (D/L=0.1)**

This category of beams has been studied through models G11 and G16 for square and rectangular openings respectively. Figures 15 to 18 illustrate that the results of W_u according to Darwin's method allow less than FEA results for beam G11 with different web thicknesses. Also, the difference between the results decrease due to the increase in web thickness at t_w=0.5mm, W_u equals 14.48 and 16.66 kN/m according to Darwin and FEA methods respectively. W_u equals 20.22 and 22.07 kN/m for t_w=0.7mm as shown in Figures 15 and 16. This fact is clearly evident from Figure 19 where the percentage variation for beam G11 has a positive value for any web thickness and it decreases due to the increase in the web thickness.

A comparison between the results of beams G1 and G11 with square openings at D/L=0.1 and with h_o/d equal to 0.5 and 0.70 respectively is done to study the effect of opening height on the percentage variation. It is found that the percentage variation increases due to the increase in opening height for the same web thickness. For beams G1 and G11 with t_w=0.8mm, the percentage variation equals 5.33% and 7.41% at h_0/d ratio equal to 0.5 and 0.7 respectively as shown in Figures 13 and 19. The same results occur from Figures 25 and 26 for the same beams with reinforced openings. It is illustrated that Darwin's guidelines can be used for non-compact and slender steel beams which have un-reinforced or reinforced square openings with height-to-beam depth ratio (h_o/d) equal to 0.70.

Opposite to the results of beam G16 with un-reinforced rectangular opening and h_0/d equal to 0.7, the results of W_u according to Darwin's method are higher than FEA results for this beam with different web thicknesses as shown in Figures 17 and 18. This led to make the percentage variation of this beam has a negative value for any web thickness as shown in Figure 20. It is observed that the percentage variation increase due to the increase in its web thickness where the percentage variation equals -4.72% and 12.33% for t_w=0.5mm and 8mm respectively. For the case of the same beam with reinforced opening, it is found that the results of W_u according to Darwin's method are smaller than the FEA results as shown in Figures 23 and 24 and then, the percentage variation has a positive value for any web thickness. It is illustrated that the Darwin's guidelines cannot be used for non-compact and slender steel beams which have un-reinforced rectangular opening with height-to-beam depth ratio (h_o/d) equal to 0.70 and located at the zone of high shear (D/L=0.1). When its opening is reinforced, Darwin guidelines can be used.

- **Beams with opening at high moment zone (D/L=0.4-0.5)**

This category of beams has been studied through models G14 and G15 for square openings and models G19 and G20 for rectangular openings with $a_0/h_0=2$. The results of Darwin and FEA for each beam with un-reinforced opening and different web thicknesses are shown in Figures 15 to 18. It is illustrated that the results of the two methods are close for these beams except beam G19 where the relations between the variation percentage of Wu for beams G14, G15 and G20 and their web thickness is constant with small negative values ranging from -1.82% to -4.19% as shown in Figures 19 and 20. It can properly be attributed to the same reason which was mentioned before in the case of beams with openings at the same zone with $h_0/d=0.5$. In case of beam G19 with un-reinforced rectangular openings at D/L=0.4, it is found that the percentage variation has a high negative value where it equals -13.35 % for t_w=8mm and it decreases due to the decrease in the web thickness where it equals -4.72% for t_w=0.5mm as shown in Figure 22. Also, the same thing can be observed from Figure 24 for beam G19 with reinforced rectangular opening where t_w=8mm, the failure distributed load W_u equals 37.24 and 32.25 kN/m according to Darwin's and FEA methods respectively when the percentage of variation equals -3.1%.

From the above it can be concluded that Darwin's guidelines can be used for non-compact and slender steel beams which have un-reinforced or reinforced openings with height-to-beam depth ratio (h_o/d) equal to 0.70 for square openings when the openings are located at the high moment zone (D/L=0.4 and 0.5). Also, for rectangular openings for (D/L= 0.5). Yet, it cannot be used for rectangular openings at (D/L= 0.4) with opening height equal to 0.7 the beam depth.

- **Beams with opening at moment-shear combination zone (D/L=0.2 – 0.3)**

This category of beams have been studied through models G12 and G13 for square openings and models G17 and G18 for rectangular openings with $a_0/h_0=2$. The results of Darwin and FEA are shown in Figures 15 to 18. It is observed that the results of the two methods for models G13, G17 and G18 have clear differences for any web thickness. For beam G18 at t_w=8mm the failure load W_u equals 31.41 and 30.25 kN/m according to Darwin's and FEA methods respectively and the percentage variation equals -11.23% as shown in Figures 19 and 20. It is shown that the percentage variation between the results of the two methods for these beams has negative values. For beam G12 it is found that the percentage variation has a positive value equal to 13.74% and 2.68% at t_w=5 and 8mm respectively as shown in Figure 19. It is not clear how the similarity between the shapes of the percentage variation charts for beams G11 and G12 when increasing the thickness of the beam web.

From the above it is clear that Darwin's guidelines cannot be used for steel beams with non-compact and slender webs and having un-reinforced openings with height-to-beam depth ratio (h_o/d) equal to 0.70 and located at the zone of combination between moment and shear (D/L=0.2 – 0.3). Yet, it can be used when the opening is square near the high shear zone at (D/L=0.2).

In general, from a review of Darwin's guidelines, it is found that the interaction equation (Eq. 1) consists of two terms, one term shows the effect of moment and the other indicates the effect of shear. Based on that, when the opening is located at a high moment zone (at D/L=0.5), the shear nearly equals zero and then the equation becomes mainly dependent on the moment term. From the comparison between Darwin's and FEA methods for beams having openings at mid span, it is found that the percentage variation is very close for the two methods. Therefore, it can be concluded that the accuracy of the moment term in equation (1) is acceptable in cases of beams with non-compact and slender webs.

Vice versa, in case of openings located at high shear zone (D/L=0.1), equation (1) of Darwin's guidelines becomes mainly dependent on the shear term because the percentage of variations between the results of the two methods have high values therefore, it can be concluded that the accuracy of the shear term in equation (1) is not acceptable in cases of beams with non-compact and slender webs and must be corrected. This can be assessed from the results of moment-shear combination zone, where the percentage variations have high negative values.

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VIII. Conclusions

In this paper, a finite element model is presented to model perforated beams with non-compact and slender webs subjected to uniform load. The results of the model are used to check the accuracy of using Darwin's guidelines for different cases of perforated beams with non-compact and slender webs. The main conclusions obtained from this research can be summarized into the following:

- Darwin's guidelines must be modified so as be used in cases of perforated beams with non-compact and slender webs; especially the shear term in the interaction equation
- Darwin's guidelines give conservative results and can be used for non-compact and slender web beams with un-reinforced or reinforced square openings with height (h_o) up to 0.7 of the beam depth (d) when the opening is located at 10% of the beam span from the support yet, it can be applicable for rectangular openings with aspect ratio (a_o/h_o) equal to 2.0, when the opening height not exceeding 0.5 the beam depth.
- Darwin's guidelines cannot be used for non-compact and slender web beams which have un-reinforced rectangular openings with height-to-beam depth ratio (h_o/d) equal to 0.70 when the opening is located at 10% of the beam span from the support because Darwin's guidelines give values for beam load capacity more than the accurate values when the opening is reinforced, the accuracy of Darwin's guidelines is accepted and can be used.
- Darwin's guidelines may be used for non-compact and slender web beams which have un-reinforced or reinforced openings with height-to-beam depth ratio (ho/d) up to 0.70 for square opening and located at a high moment zone (D/L=0.4 and 0.5) because the results of Darwin guidelines for the load capacities of these beams are close with those obtained by the FEA.
- Darwin's guidelines can be used for non-compact and slender web beams which have un-reinforced or reinforced openings with height-to-beam depth ratio (h_o/d) equal to 0.50 for rectangular openings with aspect ratio (a_o/h_o) up to 2.0 when the opening is located at high moment zone (D/L= 0.5) but, it cannot be used for a rectangular openings at (D/L= 0.4).
- Darwin's guidelines cannot be used for non-compact and slender web beams with un-reinforced or reinforced square and rectangular openings with height-to-beam depth ratio (h_o/d) up to 0.70 located at the combination zone between moment and shear (D/L=0.2 – 0.3) especially for rectangular openings where, Darwin's guidelines give values more than the accurate results obtained by the F.E.A.

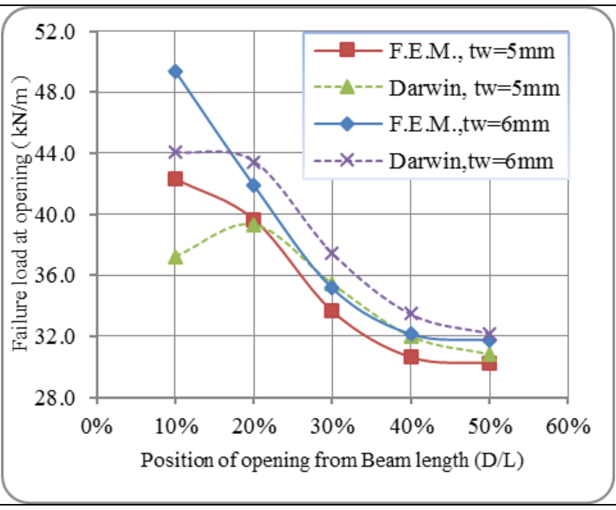


Fig. 9 Relation between failure load at opening and opening position for beams G1 to G5 without reinforcement

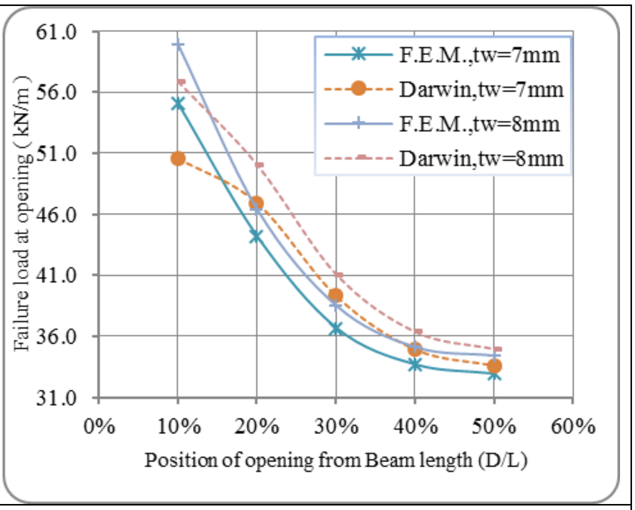


Fig. 10 Relation between failure load at opening and opening position for beams G1 to G5 without reinforcement

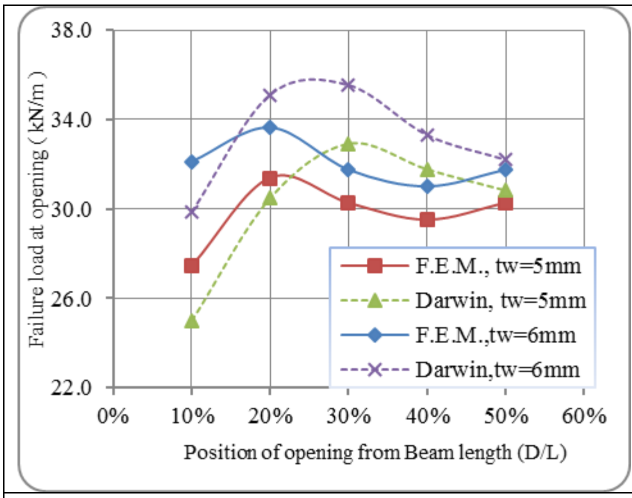


Fig. 11 Relation between failure load at opening and opening position for beams G6 to G10 without reinforcement

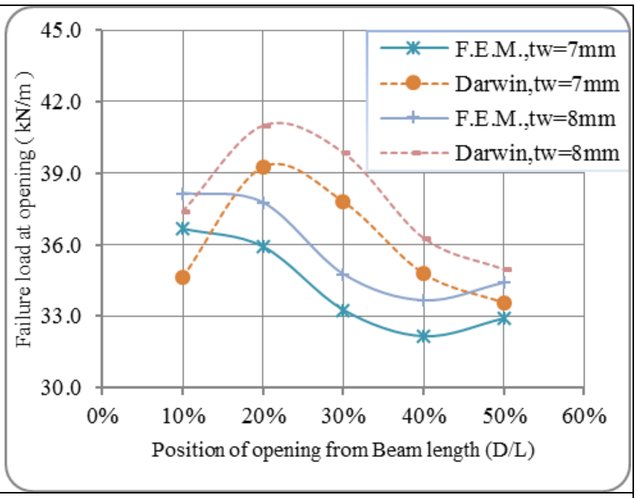


Fig. 12 Relation between failure load at opening and opening position for beams G6 to G10 without reinforcement

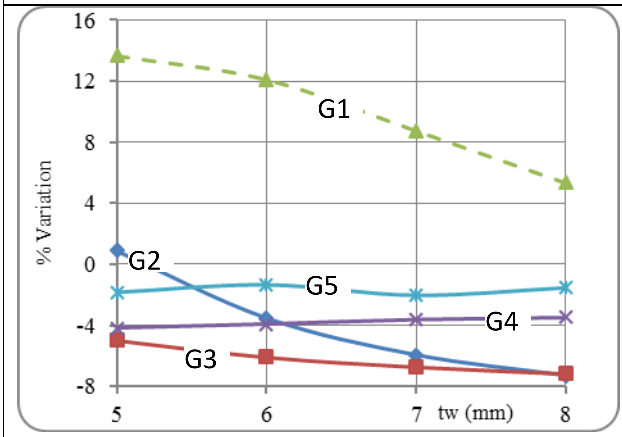


Fig. 13 Relation between %Variation between results of Darwin and FEA for G1 to G5 without reinforcement

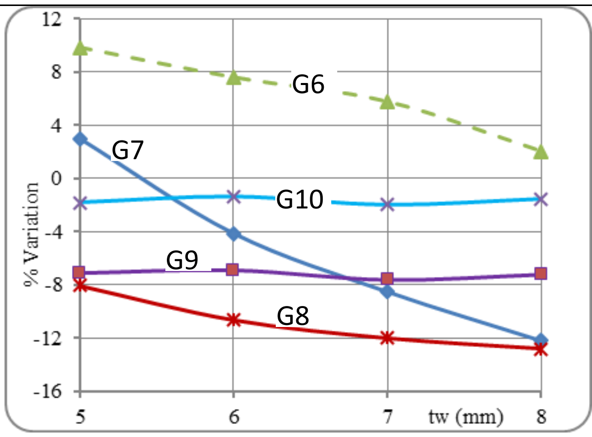


Fig. 14 Relation between %Variation between results of Darwin and FEA for G6 to G10 without reinforcement

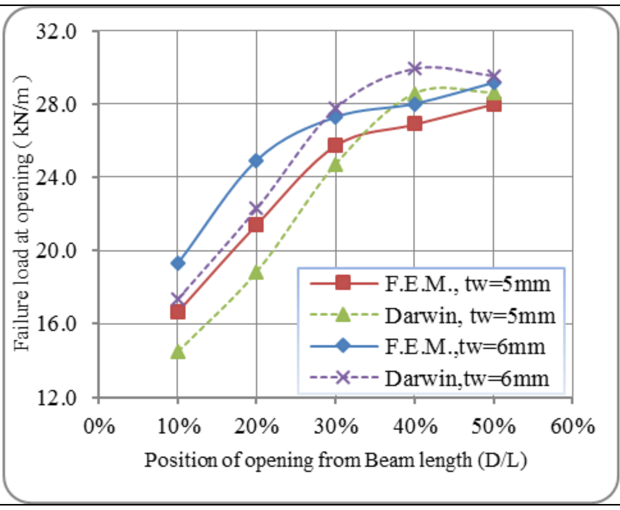


Fig. 15 Relation between failure load at opening and opening position for beams G11 to G15 without reinforcement

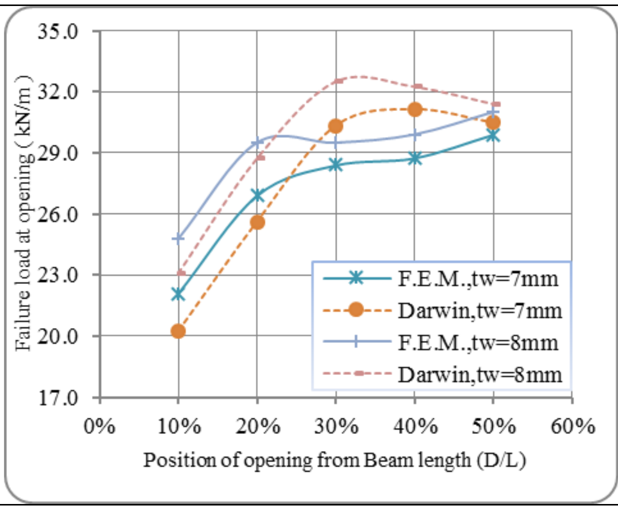


Fig. 16 Relation between failure load at opening and opening position for beams G11 to G15 without reinforcement

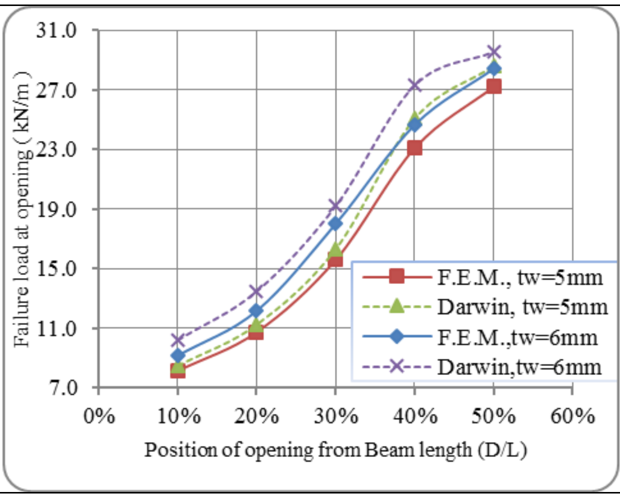


Fig. 17 Relation between failure load at opening and opening position for beams G16 to G20 without reinforcement

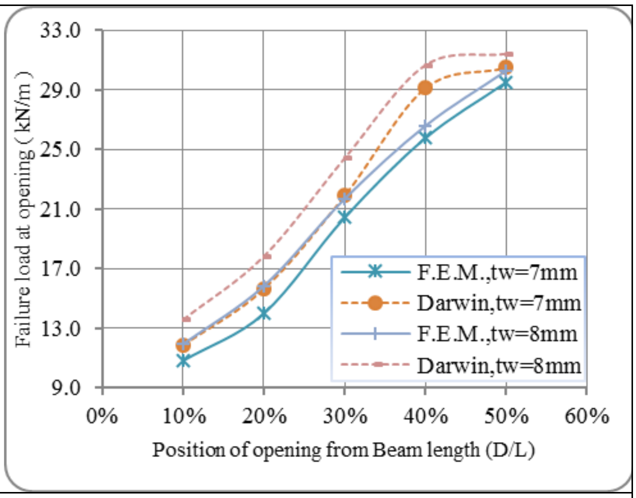


Fig. 18 Relation between failure load at opening and opening position for beams G16 to G20 without reinforcement

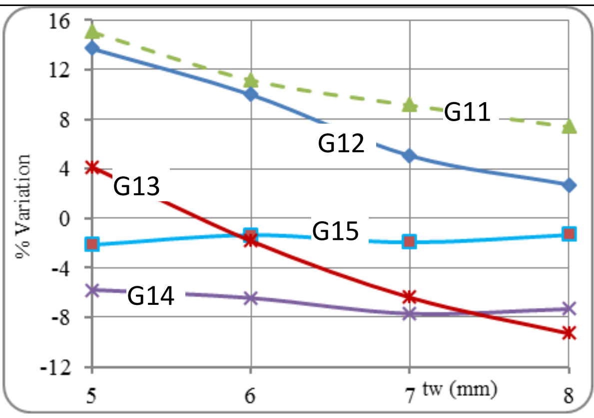


Fig. 19 Relation between %Variation between results of Darwin and FEA for G11 to G15 without reinforcement

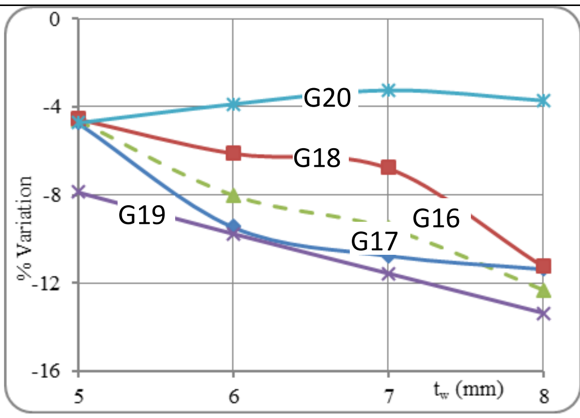


Fig. 20 Relation between %Variation between results of Darwin and FEA for G16 to G20 without reinforcement

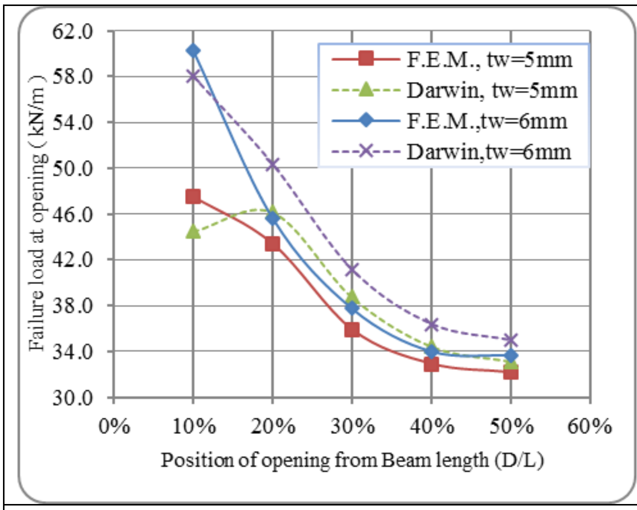


Fig. 21 Relation between failure load at opening and opening position for beams G1 to G5 with reinforcement

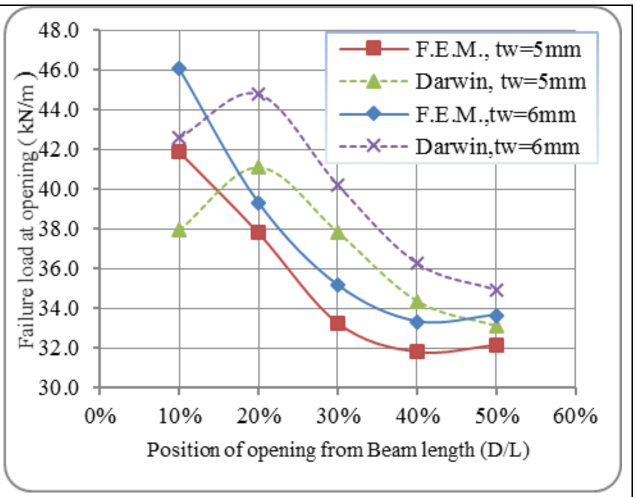
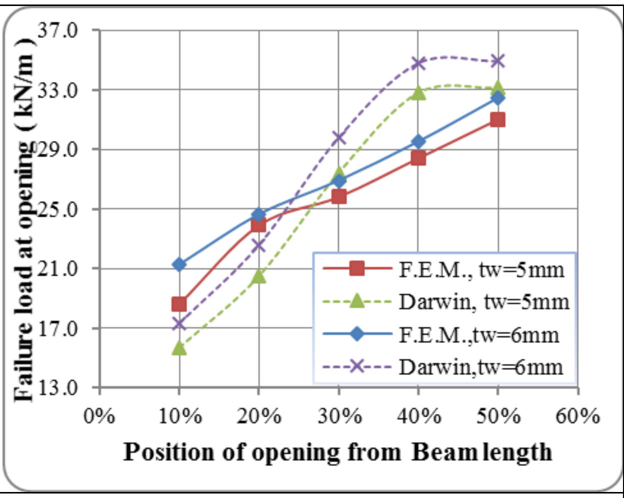


Fig. 22 Relation between failure load at opening and opening position for beams G6 to G10 with reinforcement



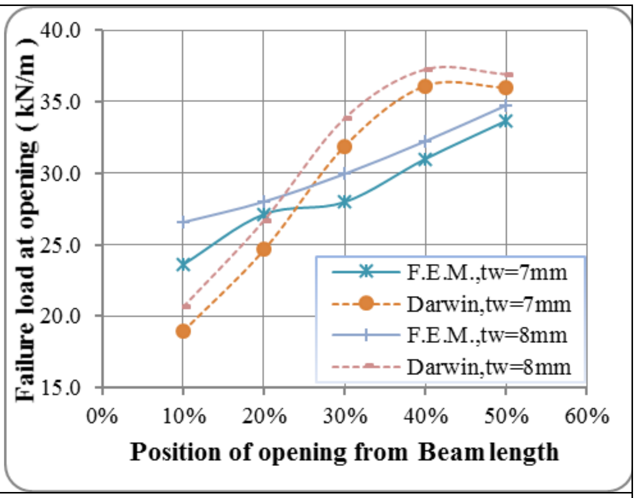


Fig. 23 Relation between failure load at opening and opening position for beams G16 to G20 with reinforcement

Fig. 24 Relation between failure load at opening and opening position for beams G16 to G20 with reinforcement

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References

[1]. Congdon, J. G., and Redwood, R.G. "Plastic behavior of beams with reinforced holes", Journal of the Structural Division 1970; ASCE Vol. 96, No. ST9: 1933-1956.
[2]. Cooper P. B. and Snell R. R. "Tests on beams with reinforced web openings", Journal of the Structural Division 1972; 98- ST3: 612-632.
[3]. Lupien R. and Redwood R. G. "Steel beams with web openings reinforced on one side", The National Research Council of Canada, Can. J. Civ. Eng. 1978; 5: 451-461.
[4]. Redwood R. G. and Cho SH. "Design of steel and composite beams with web openings", J. construction steel 1993; 25:23-41.
[5]. Prakash B. D., Gupta L. M., Pachpor P. D., and Deshpande N. V. "Strengthening of steel beam around rectangular web openings", International Journal of Engineering Science and Technology (IJEST) 2011, ISSN: 0975-5462, Vol.3 No.2:1130-1136.
[6]. Akwasi M. A. and Hsiao J. K. "Behavior of wide flange beams with reinforced web openings " M.Sc. Thesis, Southern Illinois University Carbondale, 2012.
[7]. Abdul Gabar M. S. "Behavior of steel plate girders with web openings loaded in Shear" Eng. &Tech. Journal 2013, 31, Part (A): No.15.
[8]. Darehshouri S.F., Shanmugam N. E. and Osman S.A. "An analytical method for ultimate shear strength of composite plate girders with web openings" Engineering Structures j. 2013; 56: 610–620.
[9]. Darwin, D. and Donahey R.C. "LRFD for composite beams with unreinforced web openings." Struct. Eng., ASCE 1988; 114 (3): 535-552.
[10]. Darwin D. and Lucas W.C. "LRFD for steel and composite beams with web openings." Struct. Eng., ASCE 1990; 116(6): 1579-1593.
[11]. Darwin D. "Steel and composite beams with web openings - American Institute of Steel Construction'' Steel Design guide series 1990; No. 2, Chicago, IL.
[12]. American Institute of steel construction. Manual of steel construction: Load and resistance factor design specification for structural steel buildings. AISC-LRFD, 2005.
[13]. ANSYS, finite element program, Swanson Analysis System, Inc., Release 12.1, 2009.
[14]. T.C.H. Liu and K.F. Chung, 2003. "Steel Beams with Large Web Opening of Various Shape and Size: finite element investigation "Journal of Constructional Steel Research"59, 1159-1176.
[15]. Mahmoud S. M. "Strengthening of web openings in steel girders" M.Sc. Thesis, Helwan University Cairo, 2015.