

Strengthening of web opening in non-compact steel girders

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Abstract: The use of web openings to pass the utilities of structures through steel beams can help in minimizing buildings height and hence decreasing operational and maintenance costs. However, web openings can significantly reduce the shear and bending strength capacity of the steel beams. The last researches focused on the study of perforated beams with compact steel webs to exclude the effect of local buckling. Therefore, the objective of this paper is to study the effect of web openings on the capacity of beams having non-compact sections in order to determine the critical positions of web openings. Thus, supposing the suitable technique for web strengthening according to shape, size and location of the opening with respect to beam length. The study is focused on the non-compact and slender web beams due to its economical and common uses. The study also investigated the efficiency of different types of stiffeners welded at the opening regions in order to increase the beams ultimate load carrying capacity. The obtained results showed that the longitudinal stiffeners is the best strengthening system. The analytical investigation utilizes nonlinear finite element modeling techniques using ANSYS program, considering both geometric and material nonlinearities. The results of the finite element models were verified with the results of experimental tests found in literature.

Keywords: Non-Linear Analysis, Steel Structures, Web Openings, Perforated Steel Girder, Vierendeel Mechanism, Web Reinforcement, Non-compact Web and Finite Element Method.

I. Introduction

Passing of utilities and services such as ventilation ducts, air condition ducts, electrical and data communication systems, fire protection systems, heating and cooling systems and instrumentation cables may be needed to increasing the floor height. This leads to additional cost, beside it is unacceptable choice from the architectural view, where there is a strict requirement on the story height of many buildings especially in modern multistory buildings. Therefore, openings should be provided in the web of steel girders to permit passing the utilities within the constructional depth of the floor which result minimizing the floor height to give a good architectural emphasis. However, the existence of web openings may have a significant passive effect, where the beam may be weakened in the vicinity of the opening due to the reduction in the beam strength which will occur. The method of using the shear-moment interaction curves was widely used in the past, but the methodology is now enhanced by a comprehensive finite element study. Many researchers have surveyed the behavior, strength, and establish a design methodology for designing beams without or with reinforced web openings. Recently, researchers tend to study the behavior and determine the load capacity for different types of perforated compact steel beams under distributed and concentrated loads. Congdon and Redwood^[1] carried out tests on a beam with a compact web having a single reinforced rectangular opening to estimate the strength of beams with reinforced rectangular holes assuming perfectly plastic behavior. Moreover, they estimated the required area of reinforcement in order to achieve the maximum shear carrying capacity of the section. Cooper and Snell^[2] conducted an experimental investigation on sixteen simply supported beams of A36 steel W12x45 shapes. They carried out the tests by subjecting the beams to a single concentrated load at mid span under various moment-to-shear ratio to obtain the elastic stresses in the vicinity of web openings. They found that the basis of vierendeel method of analysis to calculate the normal stresses at the perforated section was in good agreement with the measured experimental normal stresses. The horizontal shear stresses calculated by the vierendeel method did not match well with the measured shear stresses. Lupien and Redwood^[3] conducted an experimental investigation on six simply supported beams with mid depth rectangular web openings. The openings were reinforced horizontally from one side of the beam web which was considered as slender. They tested the beams under various moment-to-shear ratios to study the efficiency and effect of one sided reinforcement for the opening to gain from its economy in welding and handling. They found that there are some situations where the reinforcement placed on one side of the web opening could be used. Also, they found that the necessary anchorage length of the reinforcement will normally be greater than for the same area symmetrically placed. Darwin^[4] is 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^[5]. This design guide presents a unified approach to the design of

structural steel members with reinforced or unreinforced web openings. Redwood and Cho SH. [6] developed a general method of analysis for the design of steel and composite beams with web openings. They investigated the behavior of steel and composite beams with web openings and summarized a method to predict the ultimate strength and related it to the available design aids. Prakash, et al. [7] carried out a finite element analysis using ANSYS software for steel and composite beams with unreinforced and reinforced centrally single rectangular web openings. The scope of their study deals with the aspect ratio for the openings, deformation characteristics, load carrying capacities and vierendeel mechanisms. They observed that the web opening in low shear and high moment region tends to perform better than the web opening in high shear and low moment region. Also, they observed a considerable reduction in the stresses and deflections by increasing the amount of strengthening of the web opening. Akwasi [8] studied the behavior of steel beams with web openings and the variation of stresses in different cross sections of steel beams. The web opening was considered rectangular with and without reinforcement. Four FEA models were analyzed. The models were wide flange beams with solid webs, two models with web opening without reinforcement and other two models with reinforced web openings.

The aim of this research is to study the effect of web openings on the capacity of different beams having non-compact sections to determine the critical positions of web openings which need strengthening. Then, the best strengthening technique for each case of web opening for beams having non-compact sections is presented. Different parameters are considered such as opening height-to-beam depth ratio, opening shape, aspect ratio of opening, location of opening along the beam length and various reinforcement techniques around the web opening.

II. Finite Element Analysis

The most comprehensive version of ANSYS [9] provides many new functions that can simulate and analyze the mechanical behaviour of beams having web openings. After defining loadings and carrying out analyses, results can be viewed as numerical and graphical. Actually, the capacity of beam having web opening is affected by many parameters such as opening shape, dimensions, location, etc. Some of these parameters were not considered in this study such as; welds, imperfections (i.e. residual stresses), and representation of the environment (i.e., temperature). The finite element model details are described in the following subsections.

2.1 Modelling of steel parts

Four-node shell element SHELL181 is used to model all the steel elements. This includes the top and bottom flanges, webs, and steel reinforcements. It has both bending and membrane capabilities. The element has six degrees of freedom at each node; three translations in the nodal x, y, and z directions and three rotations about the nodal x, y, and z-axes. 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 the consistent behavior of the model. The considered size of mesh is equal to $d/20$ (d : is the web depth) around the opening beam, and $d/15$ for connection between web and flange of the steel beam, and at the zone near the supports. Also, the size of mesh is taken equal to $d/10$ for the rest of the beam. The meshing can be achieved by using the step of auto meshing which offers a large scale for meshing between fines to coarse mesh. The compression flange was provided by lateral restraint to prevent lateral torsional buckling. Fig. 1 shows a typical finite element mesh of perforated steel beam.

2.2 Material properties

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.

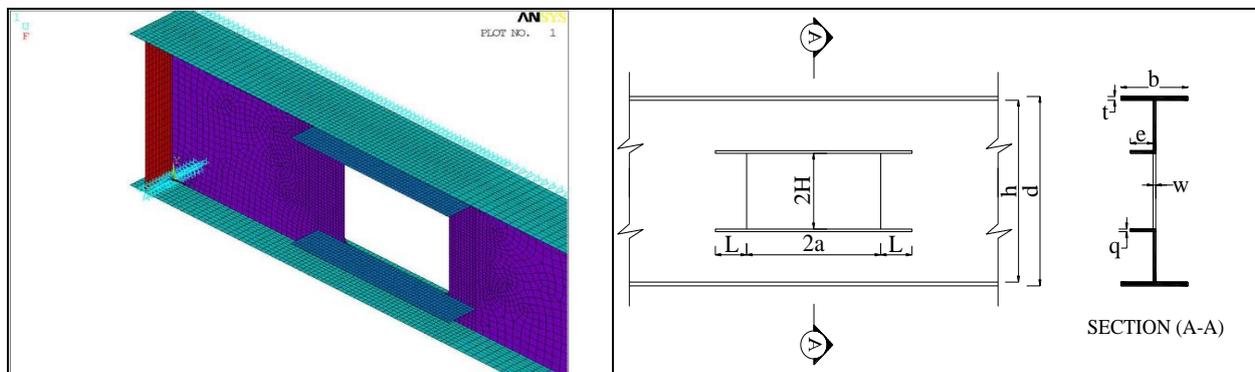


Fig. 1. Typical finite element mesh of perforated steel beam

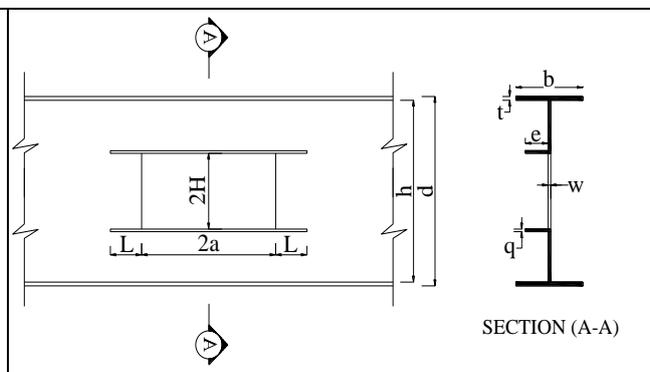


Fig. 2. Detail of beams used in verification by Lupien and Redwood [3]

Table 1: Cross section dimensions of beams tested 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 tested by Lupien and Redwood [3]

Beam	Yield stress f_y (kip/in ²)		
	Flanges	Web	Reinforcement
RL2	54.17	58.67	43.31
RL3	53.23	58.26	43.78

III. Verification of The Finite Element Model

The reliability of the proposed finite element models is checked by verifying their results with the previous experimental results which were prepared by Lupien and Redwood [3]. They tested two simply supported steel beams RL2 and RL3 with mid depth rectangular web openings as shown in Fig. 2. 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 the beam span for beams RL2 and RL3 respectively. The applied concentrated loads act at the end of one third and at the end of last third of the beam span for beam RL2, It acted at the mid of span for beam RL3. The two tested beams were modelled by using FEA as shown in Fig. 3. Figures 4 and 5 show the comparisons between the load-deflection curves resulting from the FEA by the authors and the corresponding experimental tested beams by Lupien and Redwood [3]. It can be observed from the figures that the results obtained by the proposed finite element model have a fair agreement with those obtained by Lupien and Redwood [3] with tolerances less than 2% which validates the effectiveness of the adopted numerical model.

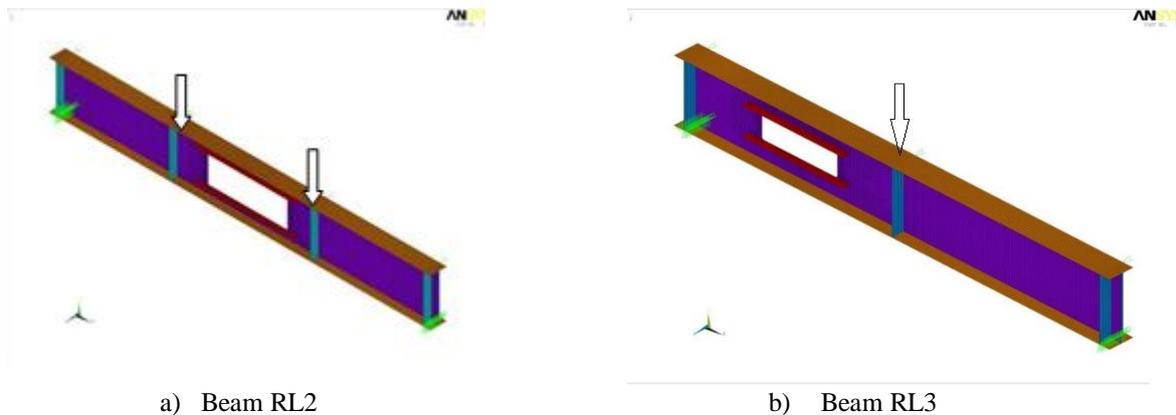


Fig. 3. Typical finite element model by authors for beams used in verification from Lupien and Redwood [3]

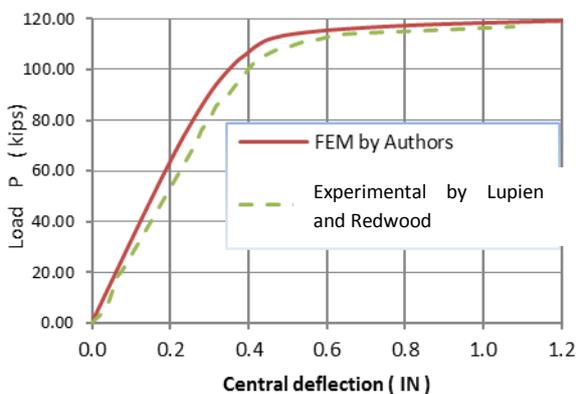


Fig. 4 (Load- deflection) curve for beam RL2

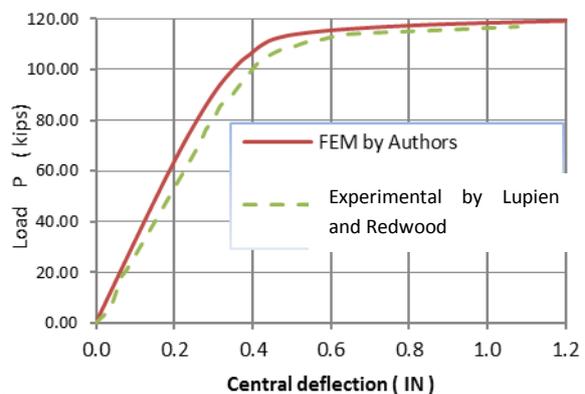


Fig. 5 (Load- deflection) curve for beam RL3

IV. Parametric Study

An extensive parametric study using the finite element model described earlier is conducted. The variations in values of load capacities were obtained for non-compact beams before and after the strengthening of web opening by using different types of reinforcement. Two different cases of loading were studied, uniform distributed load and concentrated load acting at mid of beam span in order to investigate the beam under various ratios between the moment and shear force at the centreline of the web opening. Forty nine finite element models (B1 to B49) with various geometric parameters were modelled. These models were classified into three categories. The first, beam B1 was modelled as a steel beam without opening. It was used as a guide to determine the percent of reduction in the value of the beam load capacity due to web opening. The other types were beams with web openings having rectangular shapes (B2 to B37) and circular shapes (B38 to B49). Fig. 6 shows the beam configuration and Table 3 presents the beam section properties which were used in this study.

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 plate with dimensions 500 x 80 x 10 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 the beams web depths.

There are many parameters considered to investigate their effects on the capacity of perforated beams such as the opening shape, the opening height (h_o), the opening width (a_o) and the position of the opening from the beam end support. The shape of opening is considered as a square, rectangular or circular. The opening height (h_o) to beam depth (d) ratio was taken equal to 0.25, 0.50, and 0.70. The opening width (a_o) was considered equal to one, two, and three times the opening height (h_o), where, the centre of opening assumed at distance (D) from left support as shown in Fig. 6. Four locations of the opening were considered, at (D) equal to 10%, 20%, 35%, and 50% from the beam span, whereas the ratio between the moment and shear force at these positions is varied. Tables 4 to 7 illustrate the variable parameters for the studied beams with different opening shapes (square, rectangular and circular).

Finally, the effect of five different reinforcement types as shown in Fig. 7 was studied. The relation between the failure load and the opening position (as a percentage from beam span) has been represented in the form of tables and curves.

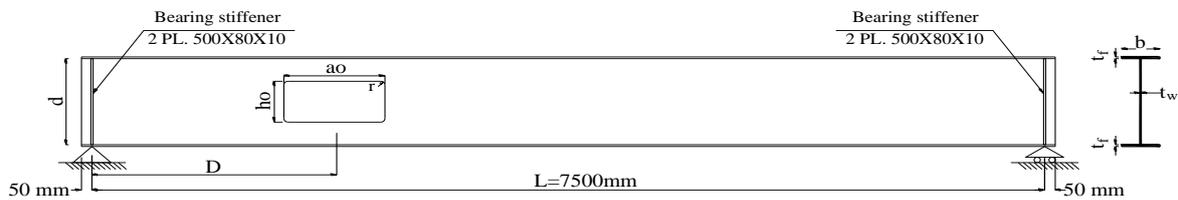


Fig. 6 Layout configuration of the studied beam

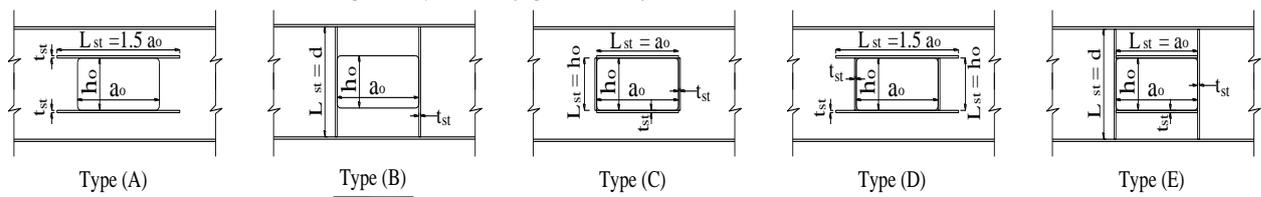


Fig. 7 Different types of web opening reinforcement

Table 3: Section properties of the studied beam

d (mm)	b (mm)	t _w (mm)	t _r (mm)	L (mm)	r (mm)	b _{st} (mm)	t _{st} (mm)	F _y (N/mm ²)
500	180	5	10	7500	20	80	8	235

Tables 4 to 7: Summary of different parameters considered in the study of beams with square, rectangular or circular openings

Table 4 : Beams with square or rectangular opening and $h_o/d = 0.25$

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L} \%$
B2	1	10
B3		20
B4		35
B5		50
B6		2
B7	20	
B8	35	
B9	50	
B10	3	
B11		20
B12		35
B13		50

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

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L} \%$
B14	1	10
B15		20
B16		35
B17		50
B18		2
B19	20	
B20	35	
B21	50	
B22	3	
B23		20
B24		35
B25		50

Table 6 : Beams with square or rectangular opening $h_o/d = 0.70$

Beam No.	$\frac{a_o}{h_o}$	$\frac{D}{L} \%$
B26	1	10
B27		20
B28		35
B29		50
B30		2
B31	20	
B32	35	
B33	50	
B34	3	
B35		20
B36		35
B37		50

Table 7 : Beams having circular opening (with diameter $=h_o$)

Beam No.	$\frac{h_o}{d}$	$\frac{D}{L} \%$
B 38	0.25	10
B 39		20
B 40		35
B 41		50
B 42	0.50	10
B 43		20
B 44		35
B 45		50
B 46	0.70	10
B 47		20
B 48		35
B 49		50

The value of failure load for each model from the aforementioned models was determined with considering the web opening without reinforcement. After that it is compared with the failure load for unperforated beam (B1). All affected models due to the web opening were strengthened by using one type from five different stiffeners methods, as shown in Figure (7). The stiffeners are classified to five types A, B, C, D and E. Where types A, B and C refer to extended horizontal stiffener above and below the opening, extended vertical stiffener left and right the opening and horizontal and vertical stiffener around the opening without extension (sleeve reinforcement) respectively. while, types D and E refer to horizontal stiffener above and below the opening in addition to un-extended vertical stiffener left and right the opening and extended vertical stiffener left and right the opening in addition to un-extended horizontal stiffener above and below the opening respectively. All stiffeners have the same dimensions (outstand dimensions, $b_{st}=80\text{mm}$ and thickness, $t_{st}=8\text{mm}$). The effect of each type from the maintained stiffeners types is studied to determine the best technique to strengthen the non-compact perforated beams.

V. Results And Discussions

First, the maximum load capacity of non-compact unperforated beam (B1) under the effect of different two cases of loading, uniform distributed load and concentrated load at mid of the beam span is found equal to 40.73kN/m and 157.0kN respectively. The maximum load capacities for non-compact perforated beams (B2) to (B49) are obtained from the FEA and are plotted as percent from the corresponding load capacity for the unperforated beam (B1) as shown in Figs (11) to (17). Second, these results are studied to demonstrate the effect of the web opening in reducing and minimizing the load capacity for each perforated beam according to the opening shape and location. Third, the beams affected due to the web opening are determined. They are tacked into consideration to study the effect of the different types of reinforcements for each case to determine the best reinforcement system that can be used to restore the loss from the beam capacity.

5.1 Perforated beams without reinforcement under uniform distributed load

As illustrated in Figures (11) and (14), it is shown that the load capacity of the perforated beam is not affected by the opening shape (square, rectangular or circular) if the opening height-to-beam depth ratio (h_o/d) equals 0.25 when the opening is located at any position from the beam span unless at mid of the beam span. The same phenomenon can be noticed for $h_o/d = 0.50$ but only for square or circular opening, as shown in Figure (12). While, a significant reduction in the beam load capacity is occurred for rectangular opening located at critical shear zone (near end support) with $h_o/d = 0.50$.

This can be explained by the moment-shear interaction equation (EQ.1) which consists of the summation of ratios between the actual straining actions (moment and shear) and the

corresponding cross section strength (bending and shear capacities). Therefore, the decrease of cross section strength against bending or shear minimizes the ability to resist a corresponding straining action (moment or shear) and the total capacity of beam is decreased as such:

$$\left(\frac{M_u}{\phi M_m}\right)^3 + \left(\frac{V_u}{\phi V_m}\right)^3 = R^3 \quad \text{where } [R \leq 1.0] \quad \text{(EQ.1)}$$

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 $M_u = 0$.
- ϕ : the resistance factor, equal to 0.90 for steel beams.

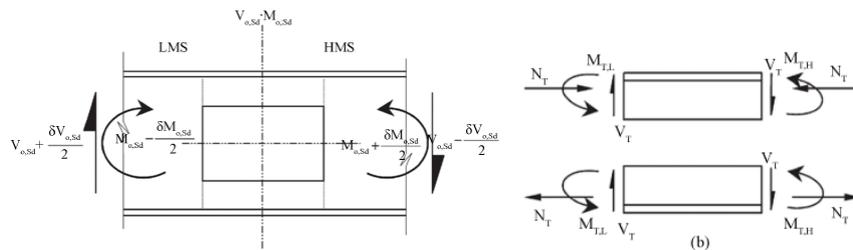


Fig. 8 Perforated section force distribution [10]

Consequently, the load capacity of beam is not affected by the opening with square or circular shape when the ratio between opening height-to-beam depth (h_o/d) up to 0.50 when it is located at any position from the beam span unless about mid of span. This is because the remaining part from the web area after opening as shown in Figure (8) is enough to resist the applied shear without any reduction in the section capacity. However, the stiffness of the beam section decreased by the association of the cross sections along the beam length especially when the opening is located at mid span.

Over and above, the increase of the opening width decreases the overall capacity of the perforated beam especially, when the opening is located near the critical shear zone because, the increase in opening width produces an additional moment (vierendeel moment) which is induced due to shear transfer along opening width, as shown in Figure 8. Therefore, failure of steel beams with web openings are frequently governed by Vierendeel collapse mechanism that occurs due to a change rate in the bending moment distribution (and consequently, the shear force) along the opening^[10]. This increase in the bending moment is usually resisted by upper and lower “Tees” through their respective local bending strengths, Figure 8^[10]. The web of the beam is “thick” and is not prone to buckling in shear under the action of the loads, the collapse is likely to be initiated by the formation of four plastic hinges, near the four corners of the hole in the web above and below the openings due to additional vierendeel moment as shown in Figure (9).

However, when the edges of the openings are un-stiffened, the non-compact or slender sections are susceptible to local buckling of the web-flange section (T section) at the horizontal edge that is in compression due to the global bending action as shown in Figure 10. The opening in such cases may be stiffened or only the elastic capacity of the web-flange section may be used. It is necessary to check for the compression zone stability of the large rectangular openings in high moment regions. This is carried out by treating it as an axially loaded column with effective length equal to that of the length of the opening (a_o)^[10].

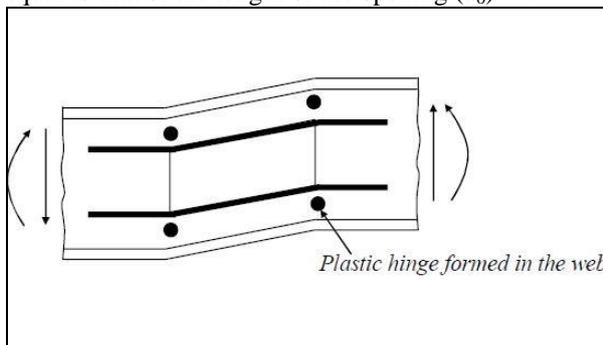


Fig.9.Details of 4-Plastic hinges formed in web

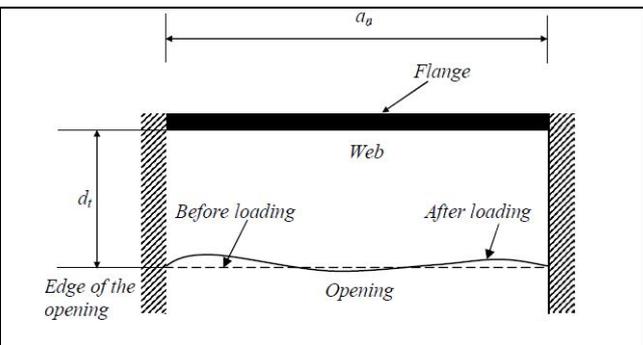


Fig. 10 local buckling of unstiffened web at the opening

For the same reason, the reduction in load capacity was even more pronounced for all perforated beams with different web opening shapes and with $h_o/d = 0.70$, as shown in Figure (13). It is observed that at a big ratio of width-to-height of opening, the loss in uniform load capacity of the beam is sharply decreased when the opening is located near support, i.e. at high shear zone (at $D/L=10\%$ and 20%) due to the increase in the additional moment (vierendeel moment) as discussed before. When providing the same opening around mid-span, i.e. at high bending moment zone (at $D/L=35\%$ and 50%) leads to slight loss in the uniform load capacity. This observation supports the recommendations of several researchers to provide the web opening around the middle of beam span for beams subjected to uniform load, where the loss in the uniform load capacity will be less than the other locations. From Figures (12) to (14), it is illustrated that when the opening at high shear zone ($D/L = 10\%$) and has circular shape with (h_o/d) equal to 0.50 and 0.70 the reduction in the uniform load capacity of beam is less about only 1%. For square opening with the same dimensions and geometric conditions, the reduction is about 20-40%. The same thing can be illustrated when the opening at high moment zone ($D/L=50\%$) but with little differences. This confirms that the beams with circular openings are presenting higher ultimate loads than the other investigated opening geometries especially, at high shear zone. Figures 25 to 27 illustrate an evolution of the Von Mises stress distribution for specimens B30, B42 and B46. It is observed that the four plastic hinges were formed in the web about opening, for any opening shape.

5.2 Perforated beams without reinforcement under concentrated load at mid span of beam

According to the nature of this case of loading, the distribution of shear force is constant along the beam span but the bending moment increases gradually to a maximum at mid span of beam. Therefore, the additional moment (vierendeel moment) which resulted due to shear transfer along opening width, will not be different due to the variation of the opening positions. Therefore, as expected, the beams with rectangular openings produce the smaller ultimate loads, i.e. about 30% less than the equivalent beams with square or circular openings as shown in Figures (15) to (18). In these beams, the Vierendeel collapse mechanism was observed in all the beams with rectangular openings independent of the beam opening position along the span. It should also be pointed out that the beams with rectangular openings located at a distance $0.50 L$ from the supports reached ultimate loads less than their equivalent beams with rectangular openings located at a distance $0.1 L$ from the supports. This issue is easily explained by the fact that the Vierendeel mechanism formation is intimately associated to the shear force magnitude at the opening, i.e. increasing the shear force magnitude at the opening reduces the beam collapse load.

Figures (15) and (18) observed that the value of beam ultimate load is not affected due to web opening with square or circular shape when the ratio between height of opening and beam depth (h_o/d) up to 0.50 at any position along the beam span except at mid span. The ultimate load at this point reduces between 7% and 17 % for square opening as well as by 4 % and 16 % for circular opening with (h_o/d) ratio equals 0.25 and 0.50 respectively. So, it is recommended that the opening must not carry out at the positions of load concentrations along the beam span.

It can be observed from Figure (17) that the beam with square opening and (h_o/d) equal to 0.70 presents a collapse mode combining the Vierendeel collapse mechanism with a load application point bending collapse. For these beams, openings located at a point distancing $0.50 L$ (where L represents the beam span) from the supports produced ultimate loads less than beams with openings at $0.10 L$ from the supports. This fact indicates that the bending stresses begin to play a significant in these beam ultimate loads. Beams with circular openings presented two distinct collapse modes. The beams with openings located at a distance $0.10 L$ from the supports had their collapse associated to a Vierendeel mechanism collapse. The Vierendeel moment is minimum in case of circular opening where the translation of shear on both sides of the opening is very smooth. Therefore the circular geometry enables the beams to sustain higher ultimate loads, similar to the ultimate loads of beams without openings. And the opening did not influence the beam collapse load. Beams with circular openings located at $0.50 L$ from the supports had their collapse as an interaction of Vierendeel mechanism and load application point bending collapse. Figure 18 presents the variation of the ultimate load at the web opening center.

Moreover, it is illustrated that if the perforated beam has a rectangular opening with various rectangularity ratios (1:2 or 1:3) and the opening height-to-beam depth ratio (h_o/d) up to 0.70; then the load capacity decreased by about 60% to 80% from the beam capacity. Also it is observed that the position of opening along the beam span does not affect the beam capacity as shown in Figure (17) because the additional vierendeel moment in this case is high and steady along the beam span due to the constancy of the shear distribution along the beam span.

5.3 Perforated beams with reinforcement under uniform distributed or concentrated load

Figures (11) to (18) demonstrate that the failure load has a high reduction in its value due to the existence of square or rectangular opening with height equal to 0.5-0.7d. Despite this fact, there are situation where the use of these openings cannot be avoided. For these cases the use of stiffeners welded at the edges of the web openings is strongly recommended by practice and design standards. Aiming to verify the structural efficiency of these stiffeners, sixteen beams were simulated with different stiffener types (A, B, C, D and E). They have the same characteristics of some of the numerical simulations performed in the parametric analysis (i.e. Specimens B22 to B37). The stiffeners were modelled with the geometrical characteristics presented in Table 3, and are illustrated in Figure 7. Figures (26) to (30) show the variation in the von Mises stresses for perforated beam (B30) without stiffeners and with stiffeners types A, B, C and D. It indicates that the use of stiffeners enables a better stress redistribution along the web openings which leads to an increase of the beams load carrying capacity. The relation between the uniform failure loads for the strengthened beams and the position of the opening as a percentage from the beam span is shown in Figures (19) to (23). Table (8) presents a comparison of the ultimate loads for beams with and without stiffeners for the configuration related to specimens B22 to B37 subjected to concentrated load at mid of beam span.

The ultimate loads of the stiffened perforated beams increased with high rate especially for beams that have openings near the critical shear region. For beams with opening near the region of high moment, the ultimate load increases but with a little rate because the augmentation in load capacity of the strengthened beam mainly depends on the improvement of the shear capacity of the perforated section. When, the development of the shear capacity of the perforated section is concerned on shear transfer along the opening width to the solid cross section of the beam at left and right of the opening. This leads to decrease the additional moment (Vierendeel moment) which results due to shear transfer along the opening width. Therefore, the function of the horizontal stiffener is to transfer and distribute the shear stresses to the solid beam section on both sides of the opening. So, the usage of strengthening types (A) and (D) improves the capacity of the beam with higher ratio more than the other types. Regarding the failure loads shown in Figures (19) to (23) and Table (8), it is obvious that the augmentations of ultimate load due to the use of each type of reinforcements (A) or (D) are equal approximately. The percent of ultimate concentrated load of specimen B31 without reinforced equals 41.56% but it increases to 88% and 92.8% for the same beam with reinforcement type (A) or (D) respectively. So, it could be recommended the usage of type (A) which refers to the extended horizontal reinforcement because it is an effective type to compensate the strength loss of the beam at the perforated section and is more economic than type (D).

Meanwhile, it is clear that type (B), which refers to extended vertical stiffener left and right of the opening is inadmissible reinforcement system for any web opening at different positions. The load capacity of the perforated beam having reinforcement type (B) decreases than without reinforcement as shown in Table (8). This could be explained that the vertical stiffener causes stress concentration at the region around the web opening which leads to early failure as shown in Figures (28) and (31). In general, it could be observed from Figures (19) to (23) that the stiffeners have high efficient contribution and a substantial improvement of the ultimate loads of beams with square and rectangular openings with (ho/d) equals 0.50 only. As shown in Figure (32) the failure of beam is governed by bending mechanism at mid span point under concentrated load. For all beams having rectangular openings with (ho/d) equal to 0.70 at the critical shear zone, the use of stiffeners increases the ultimate load about 25% from their maximum values as shown in Figures (22) and (23) and Table (8) and as shown in Figures (33) and (34) where the failure of beam (B31) without or with reinforcement type (D) is governed by Vierendeel mechanism at the opening position. So, it is recommended not to use any rectangular opening with (ho/d) higher than 0.50 at the critical shear zone.

VI. Conclusions

Last searches used experimental, numerical and analytical techniques to study the effect of web openings on the capacity of different beams with compact sections. A little of these searches considered the non-compact sections. A comprehensive finite element investigation on non-compact perforated beams with rectangular, square and circular web opening shapes was carried out. The FE model was validated against experimental work found in the literature and presented herein. Two different cases of loading were considered: uniform load and one concentrated load at mid span. Analyses of perforated sections with different web opening configurations show how the Vierendeel mechanism is affected not only by the size, but also by the shape of the web opening and its location along the beam span. The effects of the critical web opening length and depth as

well as the web opening shape are presented through a parametric FE investigation. The investigation of the web openings presents some positive results that updates the current knowledge. Based on the FE model, improvements to the assessment of load carrying capacities of steel beams with large web openings are obtained by careful observation of plastic hinge formation at both sides of the opening. The effect of different opening stiffener systems is investigated and the best strengthening technique for each case of web opening was performed. The main conclusions obtained from this research can be summarized into the following:

- There is no variation observed in experimental values and finite element analysis results obtained by ANSYS.
- The load capacity of the perforated beam is not affected by the opening shape (square, rectangular or circular) if the opening height does not exceed 25% of beam depth and the opening is located at any position along the beam span unless at the mid of beam span.
- The same phenomenon can be concluded for web openings having a height equal to half of the beam depth ($h_o/d = 0.50$) only for cases of square and circular opening shapes.
- The load capacity of the perforated beam has a significant reduction, when a rectangular opening with height not exceeding 50% of beam depth and located at the critical shear zone.
- Increasing the opening width decreases the overall capacity of the perforated beam especially, when the opening is located near the critical shear zone due to the effect of additional moment (Vierendeel moment) which is induced due to shear transfer along the opening width. It is higher in case of rectangular openings than in square ones, while it is least for circular openings.
- It is observed that the failure of perforated steel beams is frequently governed by Vierendeel collapse mechanism due to the additional Vierendeel moment which is usually resisted by upper and lower “Teess” through their respective local bending strengths.
- It is necessary to check the compression zone stability of large rectangular openings in high moment regions. This is carried out by treating it as an axially loaded column with effective length equal to that of the opening length with T-section. The strength of this column is governed by its buckling behavior and the local buckling of its T-section.
- Increasing the opening width-to-height ratio (a_o/h_o) at the first third of the span sharply decreases the capacity of the perforated section while increasing this ratio at the middle third of the span slightly decreases the capacity of perforated section.
- It is recommended that the opening must not be done at the positions of load concentrations along the beam span. Because the load capacity is sharply decreased at this section.
- The load capacity of the perforated beam having a rectangular opening with various rectangularity ratios (1:2 or 1:3) and opening height-to-beam depth ratio (h_o/d) up to 0.70 is decreased about 60-80% from its full capacity.
- The beam with circular opening presents an increase of the ultimate load that cannot be discarded. Despite this beneficial effect, the Vierendeel mechanism is still the controlling collapse mode for these beams.
- Providing a single circular opening with diameter-to-beam depth ratio (h_o/d) up to 70% has a negligible effect on the capacity of the beam except at mid span when it is reduced by 8% -12 %. Therefore it is recommended to use circular openings where they present a higher ultimate load for the perforated beam than other investigated opening geometries.
- The usage of two extended horizontal stiffeners upper and lower the opening is the most effective type of reinforcement to compensate the strength loss of the beam at the perforated section. Because it transfers the shear force along the opening to the regions besides it, therefore, Vierendeel moment is decreased. Also it restrains the out-of-plane deformations of the horizontal edges of the opening. Hence the buckling strength of the remainder T-section in the compression side is increased.
- The usage of any type of horizontal stiffeners especially, the extended types A or D increases the load capacity of the perforated beam with a high rate at critical shear zone (at $D/L=10$, 20%) than at high moment zones (at $D/L=35$, 50%)
- Providing an unreinforced rectangular web opening with height to beam depth ratio (h_o/d) more than 0.25 and width-to-height ratio (a_o/h_o) up to 0.3 sharply decreases the shear capacity at the perforated section.
- Reinforcement of the web opening with vertical stiffeners has negligible effect on the capacity of the perforated section; it may cause stress concentration around the web opening which leads to early failure. Thus, it is not recommended to use vertical stiffeners to compensate the loss strength of the beam at the perforated section.

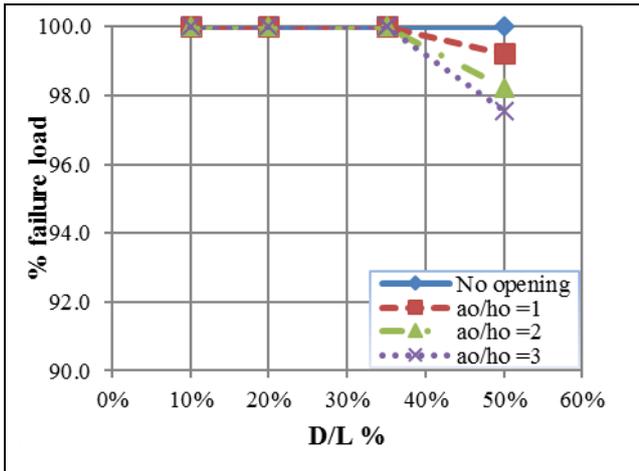


Fig. 11 max. distributed load capacity for unreinforced beams having square or rectangular openings with ($ho/d = 0.25$)

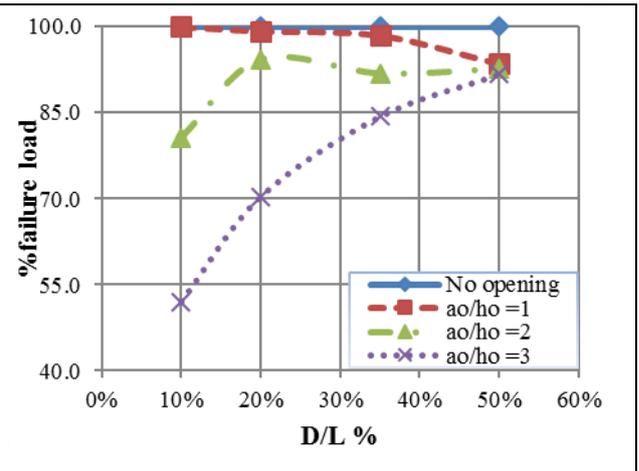


Fig. 12 max. distributed load capacity for unreinforced beams having square or rectangular openings with ($ho/d = 0.50$)

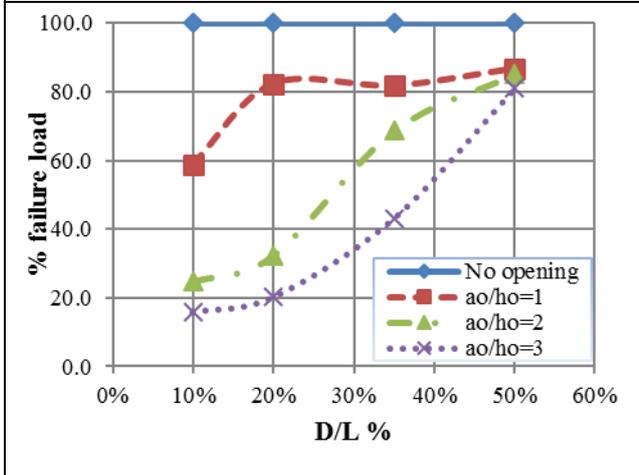


Fig. 13 max. distributed load capacity for unreinforced beams having square or rectangular openings with ($ho/d = 0.70$)

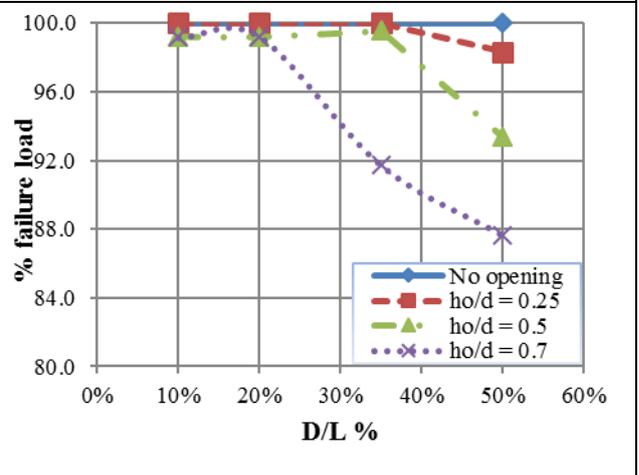


Fig. 14 max. distributed load capacity for unreinforced beams having circular openings.

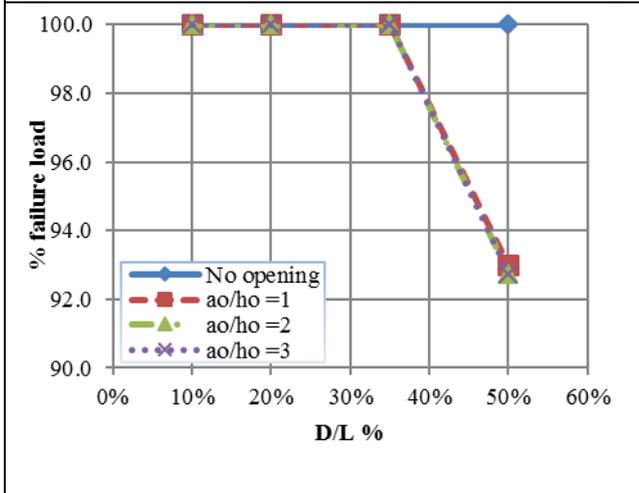


Fig. 15 max. concentrated load capacity for unreinforced beams having square or rectangular openings with ($ho/d = 0.25$)

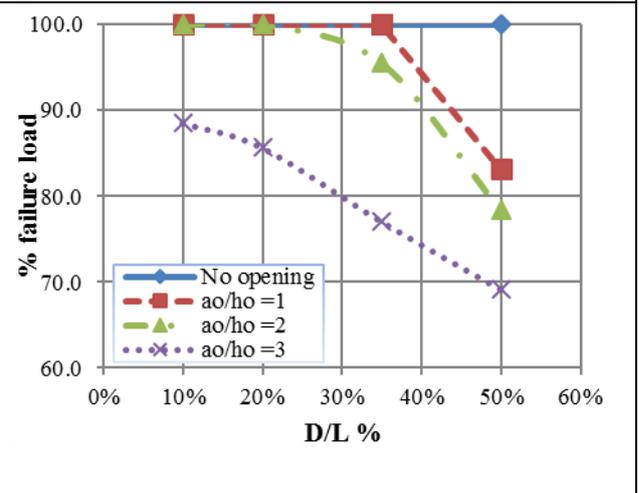


Fig. 16 max. concentrated load capacity for unreinforced beams having square or rectangular openings with ($ho/d = 0.50$)

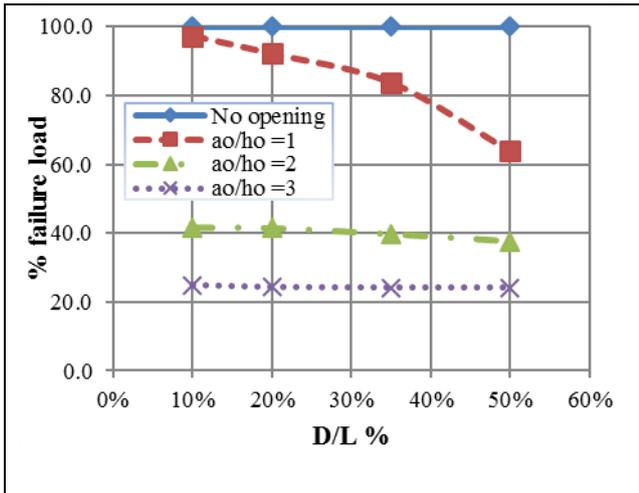


Fig. 17 max. concentrated load capacity for unreinforced beams having square or rectangular openings with ($h_o/d = 0.70$)

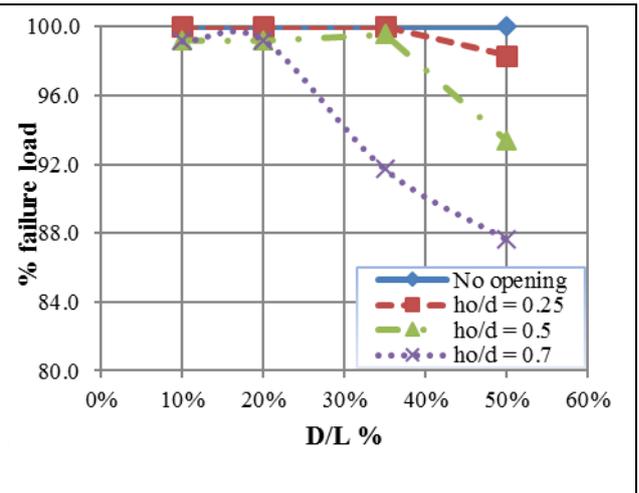


Fig. 18 max. Concentrated load capacity for unreinforced beams having circular openings.

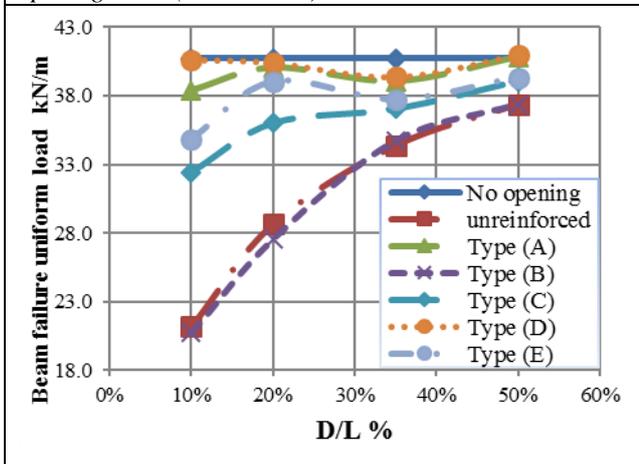


Fig. 19 max. distributed load capacity for perforated beams with ($h_o/d = 0.50$ & $a_o/h_o = 2$) due to different stiffeners

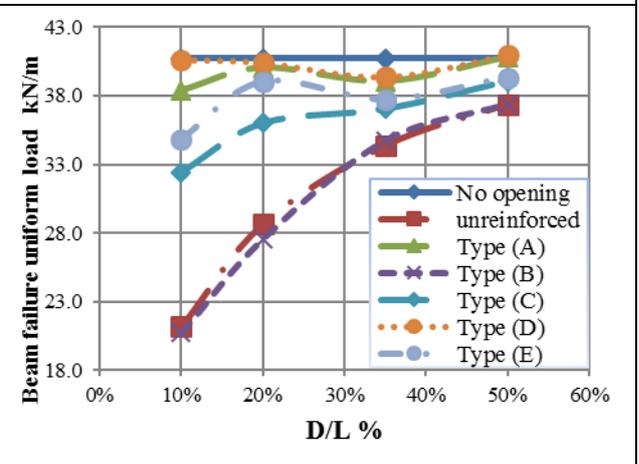


Fig. 20 max. distributed load capacity for perforated beams with ($h_o/d = 0.50$ & $a_o/h_o = 3$) due to different stiffeners

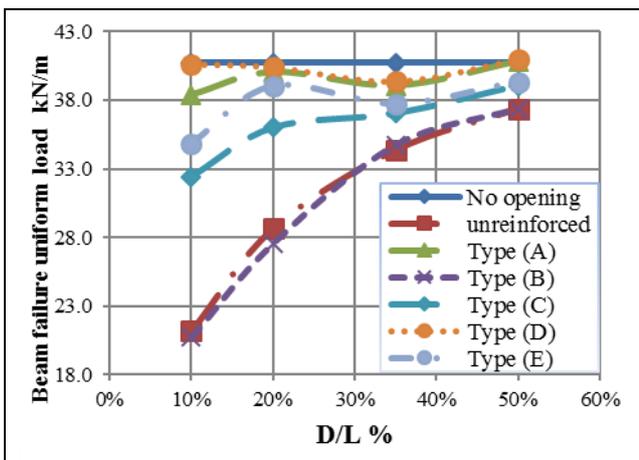


Fig. 21 max. distributed load capacity for perforated beams with ($h_o/d = 0.70$ & $a_o/h_o = 1$) due to different stiffeners

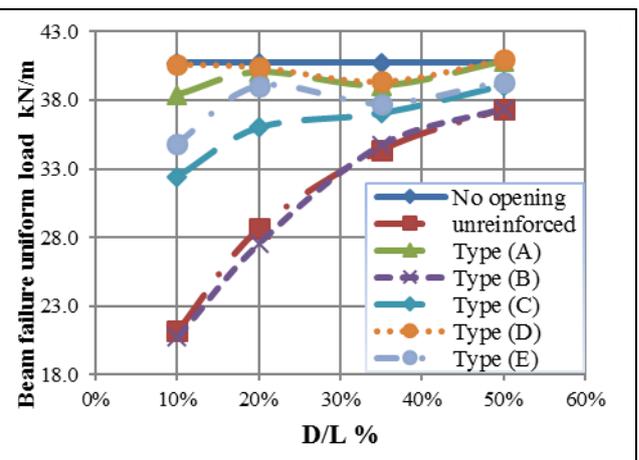


Fig. 22 max. distributed load capacity for perforated beams with ($h_o/d = 0.70$ & $a_o/h_o = 2$) due to different stiffeners

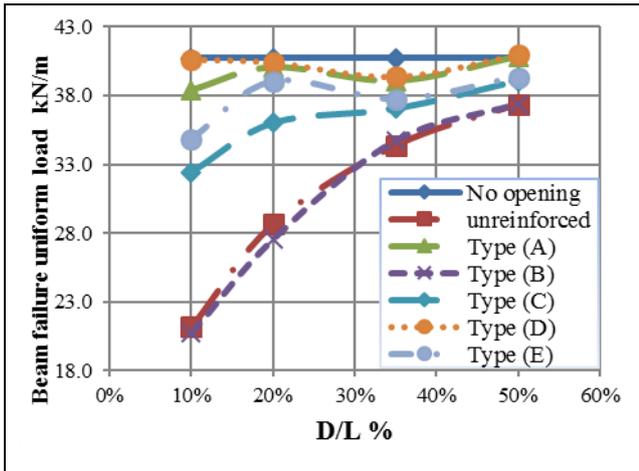


Fig. 23 max. distributed load capacity for perforated beams with ($h_o/d = 0.70$ & $a_o/h_o = 3$) due to different stiffeners

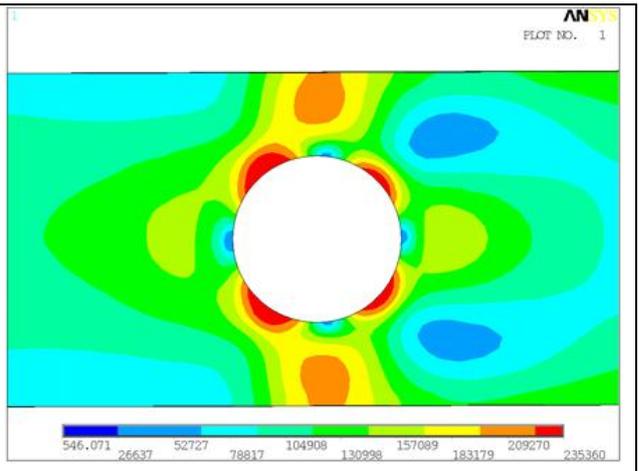


Fig. 24 Von Mises stresses (kN/m^2) for beam has a circular opening with ($h_o/d = 0.50$) without reinforcement

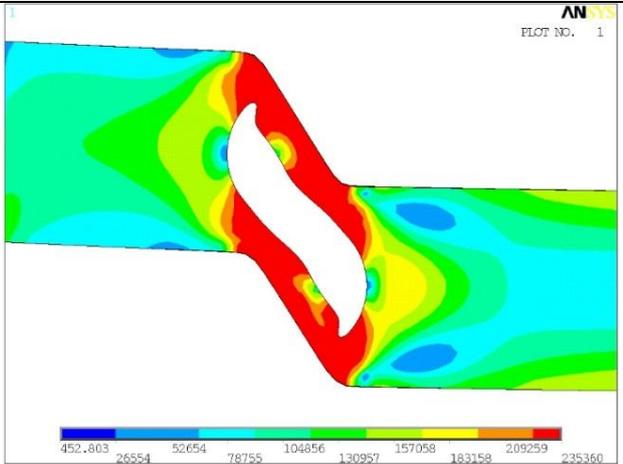


Fig. 25 Von Mises stresses (kN/m^2) for beam has a circular opening with ($h_o/d = 0.70$) without reinforcement

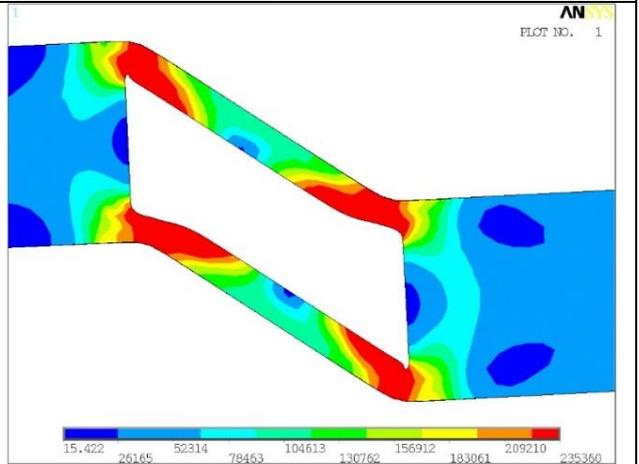


Fig.26 Von Mises stresses (kN/m^2) for beam has a rectangular opening with ($h_o/d = 0.70$ & $a_o/h_o = 2$) at ($D/L=10%$) and without reinforcement

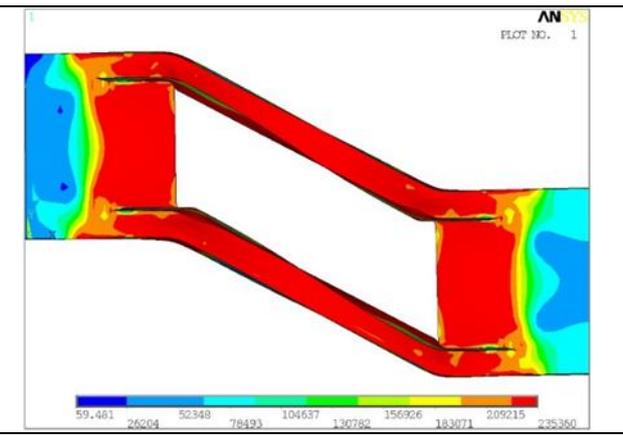


Fig. 27 Von Mises stresses (kN/m^2) for beam has a rectangular opening with ($h_o/d = 0.70$ & $a_o/h_o = 2$) at ($D/L=10%$) and with reinforcement type (A)

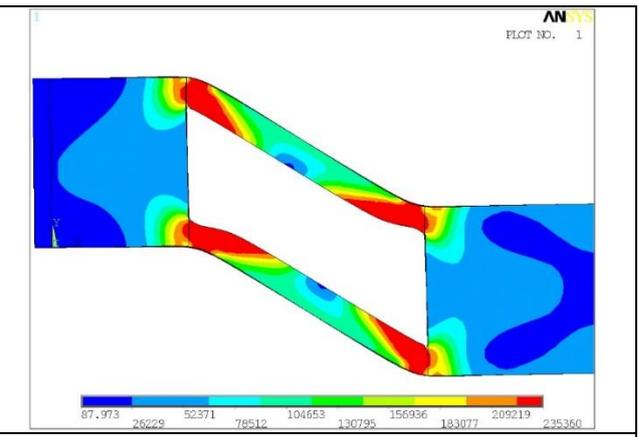


Fig. 28 Von Mises stresses (kN/m^2) for beam has a rectangular opening with ($h_o/d = 0.70$ & $a_o/h_o = 2$) at ($D/L=10%$) and reinforcement type (B)

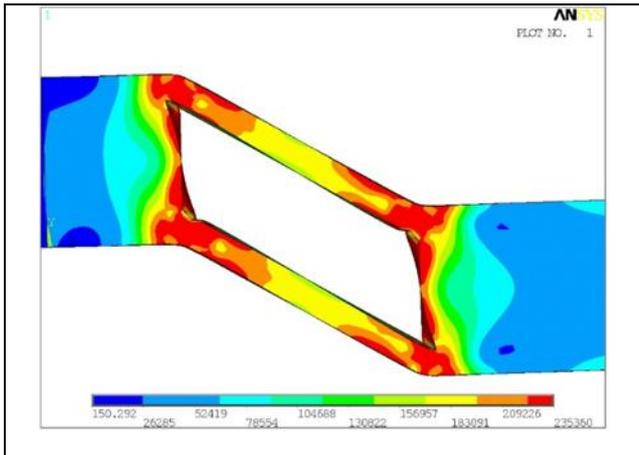


Fig. 29 Von Mises stresses (kN/m²) for beam has a rectangular opening with ($h_o/d = 0.70$ & $a_o/h_o = 2$) at ($D/L=10\%$) and reinforcement type (C)

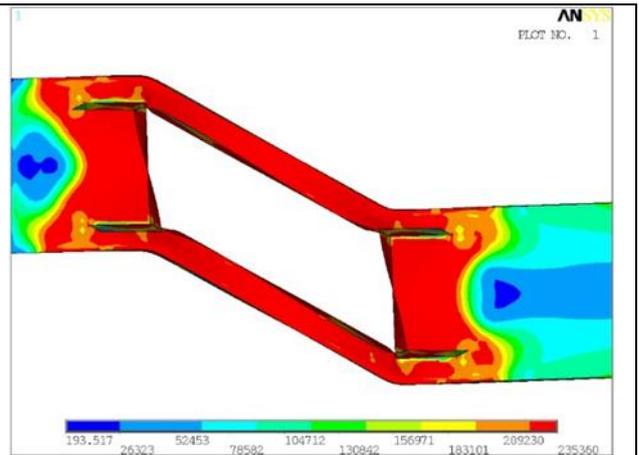


Fig. 30 Von Mises stresses (kN/m²) for beam has a rectangular opening with ($h_o/d = 0.70$ & $a_o/h_o = 2$) at ($D/L=10\%$) and reinforcement type (D)

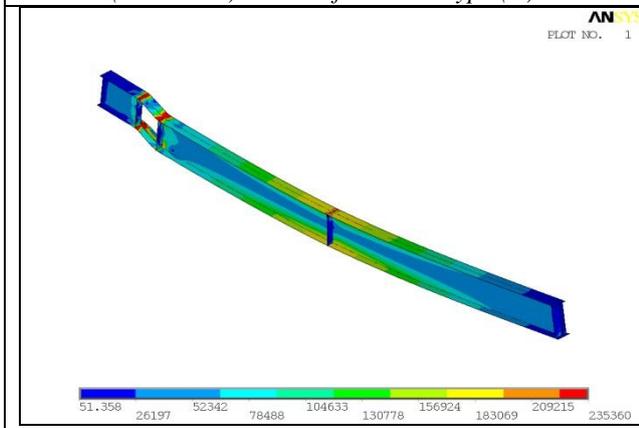


Fig. 31 Von Mises stresses (kN/m²) for beam (B26) with reinforcement Type (B) under concentrated load

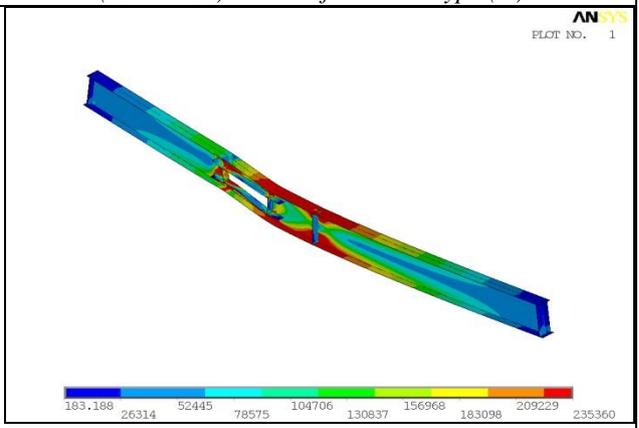


Fig. 32 Von Mises stresses (kN/m²) for beam (B20) with reinforcement Type (D) under concentrated load

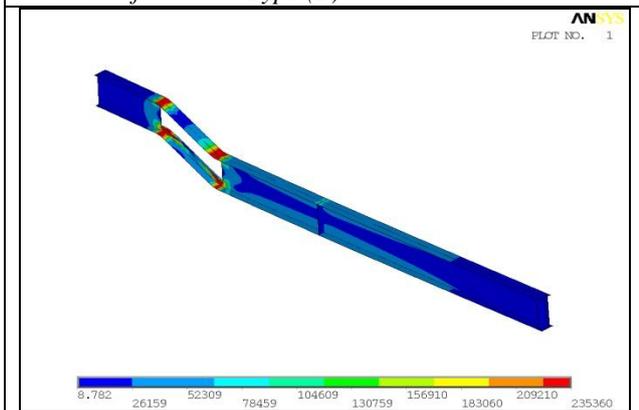


Fig. 33 Von Mises stresses(kN/m²) for beam (B31) without reinforcement under concentrated load

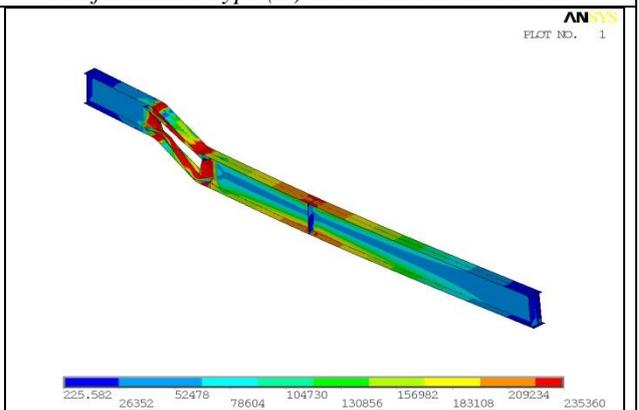


Fig. 34 Von Mises stresses (kN/m²) for beam (B31) with reinforcement type (A) under concentrated load

Table 8: Percentage of failure loads for beams B22 to B37 subjected to concentrated load with reinforcement

Beam number	% Failure load (% from failure load of unperforated beam)					
	Un-reinforced opening	opening with different reinforced systems				
		Type (A)	Type (B)	Type (C)	Type (D)	Type (E)
B 22	88.54	100.00	78.98	100.00	100.00	100.00
B 23	85.67	100.00	77.71	100.00	100.00	100.00
B 24	77.07	96.82	74.52	98.73	98.73	93.63
B 25	69.17	78.84	65.34	75.32	78.77	75.82
B 26	97.32	100.00	75.61	100.00	100.00	100.00
B 27	92.19	100.00	74.52	100.00	100.00	100.00
B 28	83.79	98.09	70.06	90.45	100.00	99.36
B 29	63.94	71.07	56.05	68.79	71.66	70.43
B 30	41.72	87.90	36.31	63.57	94.59	72.61
B 31	41.56	88.09	36.31	63.06	92.87	74.20
B 32	39.78	75.80	35.03	63.06	76.43	72.29
B 33	37.58	64.01	34.39	60.03	64.01	60.86
B 34	24.84	69.87	23.57	43.63	74.52	44.59
B 35	24.36	66.69	23.57	42.68	72.61	43.95
B 36	24.20	63.06	23.38	41.08	63.06	44.52
B 37	24.20	53.34	22.77	50.48	53.34	49.36

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