Optimum location of the square web opening in box plate girders

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Abstract

One of the most applicable sections in bridge construction is box plate girder. In order to cross the mechanical instruments and periodic maintenance it is essential to embed openings along the girder. The openings have negative effects on the capacity of the girders. This paper explores the optimum position of the web opening which results less negative effects on the plate girder ultimate resistance. So, non- linear static analysis in ABAQUS is performed on box plate girders subjected to the uniform distributed load on the top flange. To implement a comprehensive study the web slenderness, the ratio of span length to the height of the section considered as variable. Numerical results have been compared to those of the AASHTO for validity. Results exhibit that embedding the opening in the quarter of the girder span provides the least negative effect on the capacity of the girder.

Keywords: box plate girder, square web opening, non- linear static analysis, finite element

Introduction

Girders are of primary structural elements of steel bridges. Because of the existence of massive loads and long spans in bridge structure, it is needed to use of sections with huge dimensions. So, use of rolled profiles is impossible and plate girders must be constructed. The box plate girders are preferred because of high shear and torsional resistance, appropriate architectural appearance, corrosion resistance and executive costs.

The first investigations about box plate girders were performed in England and European countries (Culver and Charles, 1974, Rockey et al, 1971, "Reports of the Working Commissions", 1971, Cartledge, 1973). Most of the studies are about preventing of buckle of various parts of cross section and analyzing of the shape of the box section considering wrapping and distortion in the domain of linear behavior of materials. After that the circumstances of analyze and design of box plate girders revised several times (ASCE-AASHO Committee on Flexural Members, 1967, ASCE-AASHO Task Committee on Flexural Members , 1971, Petzold and Galambos, 1973). Parr investigated the ultimate strength of box plate girders with thick plates under flexure (Parr, 1968). Corrado performed experimental studies on the failure of two box plate girders under flexure and torsion and presented a method for estimating the ultimate strength of box plate girders (Corrado, 1971, Corrado and Yen, 1973). There are no analytical and mathematical methods for evaluating the stresses in some parts of the structure when the stress passes over the elastic limit in other parts of the girder. Yelmaz studied the ultimate strength of the plate girders using finite element approach. He investigated the stress distribution and displacement of the box plate girders in the range of the elastic and plastic behavior (Cetin Yilmaz, 1975).

None of the above mentioned studies investigated the impact of web opening on performance of box plate girders. In order to access to the inside of the box girder for periodic maintenances and crossing the mechanical instruments it is needed to create some holes in the girder. These openings increase the displacements of the beam significantly, which is mainly due to the reduction of the web shear stiffness.

Hoglund implemented some experimental studies on twelve girders with web slenderness between 200 and 300 (Hoglund, 1971). These studies proved the importance of the shear failure in perforated web girders. Narayanan investigated the effect of the square cutouts in the middle of the web panel under shear force (Narayanan and Rockey, 1981). He proposed an approximate method for predicting the ultimate capacity of the web perforated girders. The ultimate capacity can be calculated by linear interpolation of the Vierendeel effect and ultimate load of the girder without any cutouts.

So performance study of the web perforated plate girders is very important. Most of the researches is about I shape girders and there are a few studies about the impact of opening in box plate girders. Evans and shanmugam investigated the effect of square opening on the ultimate capacity of the box plate girders. They showed that the existent equations are very accurate when the failure is shear one, but if flexural failure occurs in the girder the analytical method does not present accurate estimates of the ultimate capacity (Porter et al, 1975). Shanmugam and Evans studied the effect of web opening on cellular plate girders. They exhibited that web opening has significant impact on the stresses and the strength of the beam in both linear and non- linear behavior because of the secondary effects of Vierendeel mechanism (Rockey et al, 1978). Generally there are a few investigations on the web opening effect in box plate girders.

This paper explores the ultimate strength of the box plate girders with square web opening by use of ABAQUS. To this end the non- linear static analysis is performed on the models. The geometric and material nonlinearity is considered in the analyses and for determining the equilibrium path the Riks algorithm has been utilized. In continuing the effect of opening on the ultimate capacity of the girders will be tested and the appropriate location of openings which has less negative impact will be introduced.

Modeling of the box plate girders

In this study, four classes of plate girder is modeled with 7.5, 13.5, 19.5 and 25.5 meters long which named as B1, B2, B3 and B4 respectively. The web thickness is 10, 7.5 and 6 millimeter for each class of girders. The flange thickness, height of the section and flange width is considered 14, 150 and 50 centimeters respectively in all of the models. All the girders are supported with rolled and simple supports at each end and loaded with a uniformly distributed force at the top flange. The models are stiffened with some equidistant diaphragms with 20 millimeter which are placed inside the box every 1.5 meters along the girder. The overall shape of the modeled plate girder is outlined in Fig. (1).

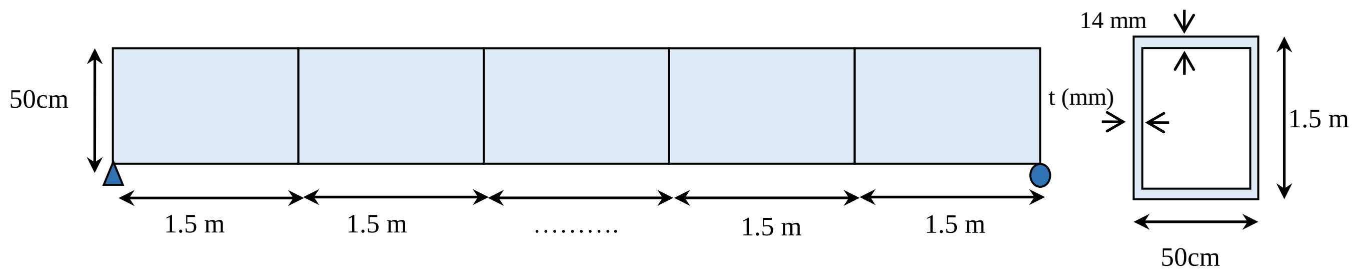

Fig.1. the overall shape of the modeled plate girder

So, twelve plate girders with similar geometry and mechanical properties will be generated expect the span length and web thickness. In order to investigate the opening effect on the behavior of the plate girders a square opening is generated in each one of the 12 models. The diameter of the opening considered as 1000 millimeters and its location placed at the end (E), middle (M) and a quarter of the girder span (Q). So 48 plate girders generated. Table (1) shows the properties of the modeled girders. For modeling the girders in ABAQUS software the S4R shell element is utilized. $f_y = 3450\,\frac{kg}{cm^2}$, $E = 2.1\times 10^6\,\frac{kg}{cm^2}$ and $\nu = 0.3$ are yield stress, modulus of elasticity and Poisson's ratio of the steel used as material in all models.

Validity

To determine the effect of opening on the behavior of the plate girders, the ultimate capacity and failure behavior of girders without cutouts must be studied first. So, plate girders without opening will be analyzed and analysis results will be compared with those from AASHTO equations for validity. As all of the models are non- compact plate girders, the ultimate capacity of the girders computes by equation (1).

$$F_{nc} = R_b R_h F_{yc} \Delta \tag{1}$$

where F_{nc} and Δ are

The coefficient R_b and R_h define as below:

$$R_b = 1 - \left(\frac{a_{wc}}{1200 + 300\,a_{wc}}\right)\left(\frac{2D_c}{t_w} - \lambda_{rw}\right), \qquad \lambda_{rw} = 5.7\sqrt{\frac{E}{F_{yc}}}, \quad a_{wc} = \frac{4D_c t_w}{b_{fc} t_{fc}} \tag{2}$$

$$R_h = 1$$

$$V_p = 0.58 F_{yw} D t_w \tag{3}$$

In equation (3) the D, t_w and F_{yw} are web depth, web thickness and yield stress of the web, respectively. The analytical and numerical results of girders without any opening are presented in table (2). As it is observed flexural failure occurs in all the models because the flexural capacities of the girders are less than shear capacity. The obtained results from analyses in ABAQUS are also well agreed with analytical results.

Table 1. Properties of the modeled plate box girders

Plate girder	Length (m)	Web thickness (mm)	Opening location
B1-6	7.5	6	Without opening
B1-6-M	7.5	6	M
B1-6-E	7.5	6	E
B1-6-Q	7.5	6	Q
B1-7.5	7.5	7.5	Without opening
B1-7.5-M	7.5	7.5	M
B1-7.5-E	7.5	7.5	E
B1-7.5-Q	7.5	7.5	Q
B1-10	7.5	10	Without opening
B1-10-M	7.5	10	M
B1-10-E	7.5	10	E
B1-10-Q	7.5	10	Q
B2-6	13.5	6	Without opening
B2-6-M	13.5	6	M
B2-6-E	13.5	6	E
B2-6-Q	13.5	6	Q
B2-7.5	13.5	7.5	Without opening
B2-7.5-M	13.5	7.5	M
B2-7.5-E	13.5	7.5	E
B2-7.5-Q	13.5	7.5	Q
B2-10	13.5	10	Without opening
B2-10-M	13.5	10	M
B2-10-E	13.5	10	E
B2-10-Q	13.5	10	Q
B3-6	19.5	6	Without opening
B3-6-M	19.5	6	M
B3-6-E	19.5	6	E
B3-6-Q	19.5	6	Q
B3-7.5	19.5	7.5	Without opening
B3-7.5-M	19.5	7.5	M
B3-7.5-E	19.5	7.5	E
B3-7.5-Q	19.5	7.5	Q
B3-10	19.5	10	Without opening
B3-10-M	19.5	10	M
B3-10-E	19.5	10	E
B3-10-Q	19.5	10	Q
B4-6	25.5	6	Without opening
B4-6-M	25.5	6	M
B4-6-E	25.5	6	E
B4-6-Q	25.5	6	Q
B4-7.5	25.5	7.5	Without opening
B4-7.5-M	25.5	7.5	M
B4-7.5-E	25.5	7.5	E
B4-7.5-Q	25.5	7.5	Q
B4-10	25.5	10	Without opening
B4-10-M	25.5	10	M
B4-10-E	25.5	10	E
B4-10-Q	25.5	10	Q

Before the analyze of the perforated girders, one of the experimental models of reference (Evans and Shanmugam, 1981) which has also analytical solution will be modeled in ABAQUS software for validity and obtained results will be compared with experimental and analytical one. The G43 steel is utilized for material of the webs, flanges and diaphragms in the experimental model. Girder has rolled and simple supports at its ends and loadings are two distributed force across the top flange at the quarter of the girder span from each end. To determine the ultimate capacity, the static load is applied increasingly to the girder. The analytical, experimental and obtained numerical results tabulated in table (3). As it is observed the numerical result is in good agreement with experimental and analytical results.

Table 2. Ultimate capacity of the girders without opening

Plate girder	P_U (Bending)	P_U (shear)	P_U (ABAQUS)
B2-6	3.86	10.65	3.72
B3-7.5	2.1	9.16	2.1
B3-6	1.85	7.4	1.88
B4-10	1.51	9.41	1.5
B4-7.5	1.23	7.1	1.25

In both models the shear buckling in end panel is occurred and tension and compression stress regions are similar. Good agreement between deformed shapes of two models emphasizes the accuracy of the analysis performed in ABAQUS.

Table 3.ultimate capacity of the girder with rectangular opening

Ultimate load capacity		
ABAQUS (ton)	analytical (ton)	experimental (ton)
12.7	13.1	12.6

Results

The behaviors of models which have similar properties with various opening locations have been compared for impact study of the opening location. . Figure (1) shows the load- displacement graph of the girder B2-7.5 with various opening locations. Embed the opening at the quarter of the girder span reduces the girder capacity about 1 percent. Opening at the middle of the girder span decreases the girder capacity about 8 percent, but if the opening embed at the end panel the failure mode of the girder turn to shear failure. Whereas the opening is at the web, so it affects significantly the girder shear capacity. As it is observed from figure (1) and table (4) we have 30 percent reduction in girder capacity.

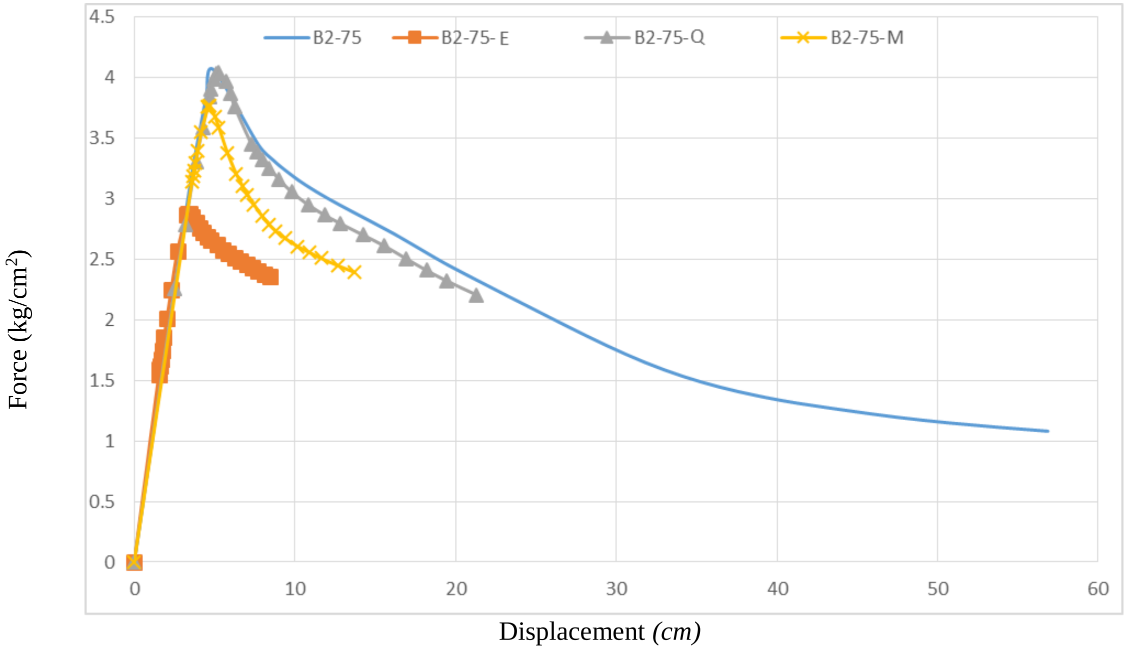

Fig.1. load- displacement graph of the girder B2-7.5 with various opening locations

Figure (11) shows the impact of the opening location on the girder capacity. Figures (11-a), (11-b) and (11-c) are related to the opening at quarter, end and the middle of the girders, respectively. From this figure, it is observed that embed the opening at the middle of the girder (location of the maximum bending) has the most effect on the capacity reduction but locate the opening at the end panel has less negative effect. The best location for opening is at the quarter of the span which cause less effects on girder capacity.

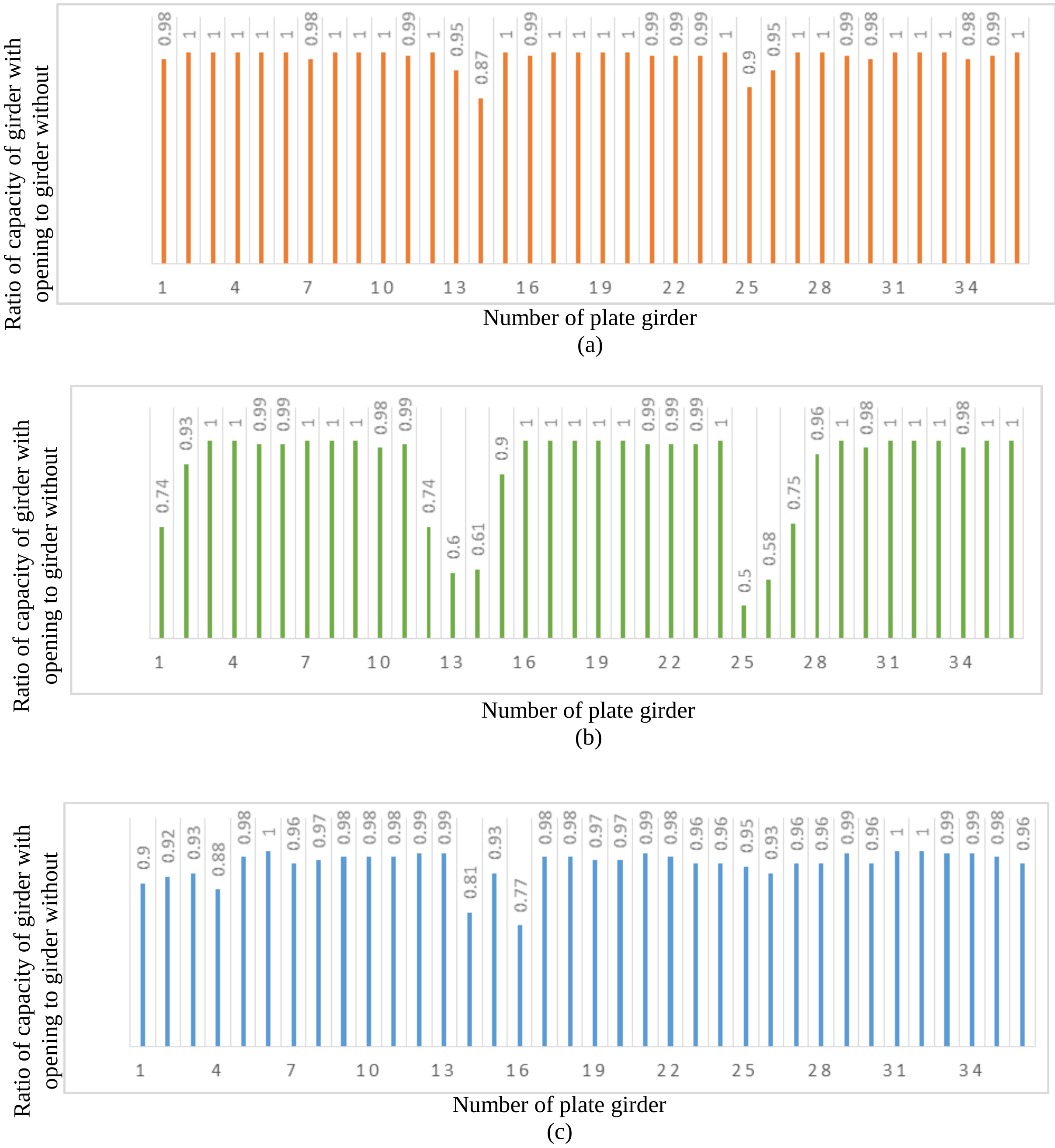

Fig.2. impact of the opening location on the girder capacity (a) opening at the quarter of the span (b) opening at the end of the span (c) opening at the middle of the span

The effect of the web slenderness effect on the girder capacity have been studied also. Figure (12) shows the capacity ratio of girders with opening to girders without opening regarding to web slenderness. Except some models showed on the left side of the graph, the web slenderness has no significant effect on the capacity of the girders with opening. The models identified with numbers 1, 2 and 3 in this figure are girders B1-E, B2-E and B3-E respectively which shear failure occur in them. It must be noted that other models have not shear failure. So the web slenderness in models with shear failure is only important. In these models the girder capacity reduces 20 percent with increasing web slenderness from 150 to 200 and 18 percent for increasing web slenderness from 200 to 250. The gray bars of the figure in contrast to the red and blue ones exhibit that the models with more slender webs descend sharply. For example the girder B1-E with web slenderness equal to 150 (the blue bar number 1) has 26 percent capacity reduction. This value decreases to 10 percent for girder B2-E which has similar properties to girder B1-E except the length of the model. In contrast the trend of capacity increase for same girders with web slenderness equal to 250 is smoother.

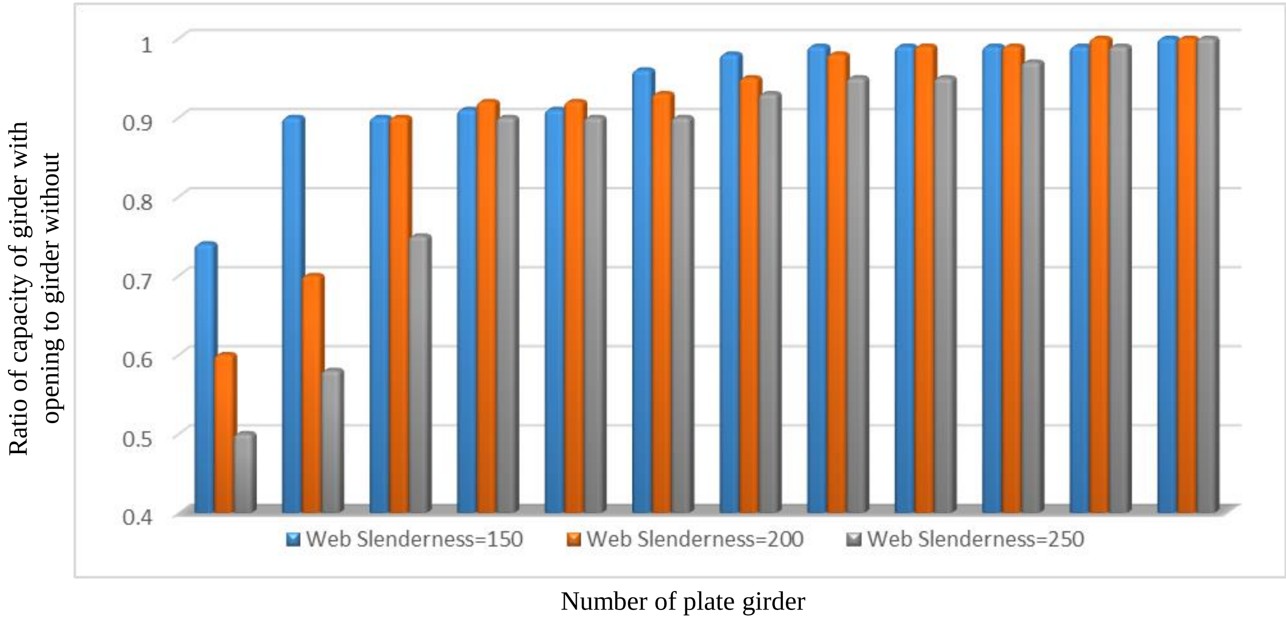

Fig.3. impact of web slenderness to the ultimate capacity of the girders with 1000 millimeter diameter

Summary and Conclusion

In this paper the effects of web opening have been studied on the behavior of plate girders.So, non- linear static analysis have been implemented on 48 plate girders. Riks algorithm has been used for applying the non- linear analyses which is able to predict post buckling behavior of structure elements. The analyses are based on finite element method. Parameters such as the location of the opening, web slenderness and ratio of bay length to the height of the section have been selected as variables to perform a comprehensive study. The 1000 millimeters diameter opening embedded at the middle, end and ¼ of the bay. Web slenderness has been considered as 150, 200 and 250 and the ratio of bay length to the height of the section is variable equal to 5,9,13 and 17.For the validity the results have been compared to those from AASHTO. So, the best place for embedding the perforation on web which causes less negative effects on plate girder capacity has been determined. Based on the results, capacity reduction of the section on average is about ten percent for 1000 mm openings. At the worst point, embedding such perforation reduces the capacity to the half and even cause to change the behavior of flexural to shear failure mode of the specimens. About the location of the opening one can state that as the openings are embedded at the webs, the best place for the perforation is at the maximum bending of the member or at the middle of the bay. But the results of this study exhibited that the location of the maximum bending is not the proper place for the web opening because this cause between 1 to 25 percent capacity reduction of the structural member. If the opening embedded at the maximum shear or support shear failure with less force will occur before flexural failure. In this situation the plate girder capacity reduces impressively such that diminishes to half in some cases. The best place for opening is a quarter of the bay which none of the bending and shear is maximum. In this case the maximum capacity reduction is about 10 percent, which is observed only in 2 percent of specimens and in other cases the capacity reduction is negligible.

References

ASCE-AASHO Committee on Flexural Members. (1967). Subcommittee on Box Girder Bridges, "Trends in the Design of Box Girder Bridges", Journal of the Structural Division, ASCE, Vol. 93, No. ST3, Proc. Paper 5278, pp. 165-180

ASCE-AASHO Task Committee on Flexural Members. (1971). Subcommittee oN Box Girders, Progress Report on Steel Box Girder Bridges", Journal of the Structural Division, ASCE, Vol. 97, No. ST4, Proc. Paper 8068, pp. 1175-1185

Cartledge, P. (Editor), (1973). Steel Box Girder Bridges, Proceedings of the International Conference Organized by the Institution of Civil Engineers in London, February 13-14.

Cetin Yilmaz. (1975). Ultimate strength of box girders by finite element method. Ph.D. Dissertation, Lehigh University.

Corrado, J. A. (1971). Ultimate Strength of Single-Span Rectangular Box Girders Ph.D. Dissertation, Lehigh University.

Corrado, J. A. and Yen, B. T. (1973). Failure Tests of Rectangular Model Steel Box Girders, Journal of the Structural Division, ASCE, Vol. 99, No. ST7.

Culver, Charles G. (1974). Steel-Box Girder Bridges Ultimate Strength Considerations, Journal of the Structural Division, ASCE, Vol. 100, No. ST12, Proc. Paper 11014, pp. 2433-2448.

Evans, H. R. , Shanmugam N. E. (1981). An exprerimental study of the ultimate load behaviour of models with web opennings small-scale steel box girder. The Journal of Strain Analysis for Engineering Design, 251-59.

Hoglund T. (1971). Strength of thin plate girders with circular or rectangular web holes without web stiffeners. Design of plate and box girders for ultimate strength. Zurich: International Association for Bridge and Structural Engineering.

International Association for Bridge and Structural Engineering, (1971). Reports of the Working Commissions", Seminar on "Design of Plate and Box Girders for Ultimate Strength, Vol. 11, London.

Narayanan R, Rockey KC. (1981). Ultimate load capacity of plate girders with webs containing circular cutouts. Proc Inst Civil Eng, Pt 2; 71:845–62.

Porter DM, Rockey KC, Evans HR. (1975). The collapse behaviour of plate girders loaded in shear. J Struct Eng; 53(8):313–25.

Petzold, E. H., Galambos, T. V. (1973). Behavior and Design of Large Steel Box Girder Bridges, Washington University, Civil and Environmental Engineering Department Research Report No. 26, Structural Division.

Parr, D. (1968). An Ultimate Strength Analysis of Box Girder Highway Bridges, Ph.D. Dissertation, New Mexico State University, May.

Rockey, K. C., Bannister, J. L., Evans, H. R. (1971). Developments in Bridge Design and Construction, Crosby Lockwood and Son, Ltd, London.

Rockey KC, Evans HR, Porter DM. (1978). A design method for prediction the collapse behaviour of plate girders. Proc Inst Civil Eng, Pt 2; 65:85–112.