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ULTIMATE SHEAR STRENGTH OF PLATE GIRDERS WITH REINFORCED WEB OPENINGS

مقاومة القص القصوى للكمرات اللوحية ذات الفتحات المقواه في العصب

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ملخص البحث

في هذا البحث تم دراسة وحساب مقاومة القص القصوى للكمرات اللوحية ذات الفتحات المستديرة أو المستطيلة في العصب. وفي هذه الدراسة تم حساب الحمل المرن الحرج وحمل الشد في عصب الكمرة عند المرحلة التالية للحمل الحرج وكذلك الأحمال والإجهادات على شفة الكمرة اللوحية وأيضا الأحمال والإجهادات الناتجة على تقويات العصب حول الفتحات.

وقد تم استخدام نظرية العناصر الدقيقة لحساب الحمل المرن الحرج والمقاومة القصوى لهذه الكمرات اللوحية ذات الفتحات المستديرة أو المستطيلة.

وفي النهاية تم مقارنة النتائج النظرية التي تم الحصول عليها في هذا البحث مع النتائج المعملية السابقة على نماذج لكمرات لوحية. وأعطت المقارنة نتائج جيدة مما يؤكد صحة ما تم دراسته.

ABSTRACT

A theoretical method is proposed for calculating the ultimate shear capacity of plate girders with reinforced web holes as the sum of four contributions, viz.

(i) the elastic critical load,
(ii) the load carried by the membrane tension in the web in the post-critical stage,
(iii) the load carried by the flange and
(iv) the load carried by the reinforcement.

Approximate formulae based on a finite element analysis are suggested for calculating the elastic critical loads in shear The membrane stresses are calculated by using the von Mises yield criterion; the contributions of the flanges and of the reinforcement are obtained form their plastic moments. Ultimate load tests on plate girder models presented previously are compared with the theoretical prediction using the analytical model described in the paper.

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From a consideration of virtual work, the ultimate shear can be evaluated in a manner similar to the one derived by Porter et al [1]:

$$V_{ult} = 2C.\sigma_t^y.t\ \sin^2\theta + \sigma_t^y t.h(\cot\theta - \cot\theta_d)\sin^2\theta - \sigma_t^y.t.d\left(1-\frac{b_c}{d}\right)\sin\theta + (\tau_{cr}).h.t \qquad (6)$$

in which;

V_{ult} ultimate shear load for perforated web,
C distance between the flange hinges,
θ angle of inclination of the tensile membrane stress, and
θ_d angle of inclination of the panel diagonal.

The value of C is obtained from $\frac{2}{\sin\theta}\sqrt{\frac{M_p}{\sigma_t^y.t}}$ and σ_t^y is evaluated by applying the Von Mises criterion :

$$\sigma_t^y = -\frac{3}{2}(\tau_{cr})\sin\theta + \sqrt{\sigma_{yw}^2 + (\tau_{cr})^2\left[\left(\tfrac{3}{2}\sin 2\theta\right)^2 - 3\right]} \qquad (7)$$

in which ,

σ_{yw} yield stress of web plate.

The values of V_{ult} obtained from equation (6) are dependent on the chosen θ ; the maximum value of V_{ult} is obtained by trial and error.

2. *PLATE GERDERS WITH REINFORCED RECTANGULAR HOLES*

It is usual to reinforce rectangular holes by welding flat plates to the web, above and below the opening (Fig. 4). The reinforcement should project beyond the edges of the hole for a length sufficient to allow the full development of the tension field; this anchorage length (l) will, therefore, depend on the dimensions of the opening, a web having a deeper opening requiring more anchorage length. Tests conducted previously [4,10] suggest that the minimum length of the reinforcement, L_r, should be 1.5 b_0 or $\sqrt{b_o^2 + d_o^2}$ whichever is larger in order that the strength lost by the hole can be fully recovered; in addition, the reinforcement should have sufficient stiffness to resist the membrane tension.

Based on extensive finite element studies, the following minimum reinforcement requirement was found to be essential in order that the buckling coefficient for the perforated web would be at least equal to that of an unperforated web:

$$\left(\frac{t_r}{t}\right)^2 \cdot \left(\frac{w_r}{h}\right) \geq 2.76\sqrt{\frac{b_o.d_o}{b.h}} \qquad (8)$$

in which;

t_r thickness of reinforcement (steel strips),
b_0 width of rectangular opening, and
d_0 depth of rectangular opening.

The second and third stages in the incremental loading for the plate girder with rectangular openings are similar to the case of circular openings. Four hinges are formed on the reinforcement as shown in Fig. (5). By the method of Virtual work, the following equation for the ultimate shear is obtained :

$$V_{ult} = 2c\sigma_t^y.t\ \sin^2\theta + \sigma_t^y.t.h\ (\cot\theta - \cot\theta_d)\sin^2\theta$$
$$-\sigma_t^y.t\sqrt{b_o^2 + d_o^2}\ \sin(\alpha+\theta)\sin\theta + 2c_r.\sigma_t^y.t.\sin^2\theta + (\tau_{cr}).h\,t \qquad (9)$$

in which;

α angle of inclination of the diagonal of the rectangular opening, and

c_r distance between hinges on the reinforcement.

In the above equation c, σ_t^y are calculated as previously indicated for circular openings . If the reinforcement had adequate end fixity, then the hinge distance c_r is obtained from

$$c_r = \frac{2}{\sin\theta}\sqrt{\frac{M_{pr}}{\sigma_t^y\ t}} \qquad (10)$$

3. *EXPERIMENTAL INVESTIGATION [4]*

Experimental work carried out previously [4] has shown that in spite of the inherent problems associated with scale effects and welding stresses, small scale models can be employed satisfactorily to assess the behaviour of plated structures. Model girders made of 1 mm webs were therefore used to carry out tests on plate girders containing reinforced web holes. Series 1 consisted of 8 shear panels containing circular holes and Series 2, of 12 shear panels with rectangular holes The parameters varied were : (a) web aspect ratio (b/h) ...(b) web slenderness (h/t) ...(c) sizes of openings and ...(d) the size of reinforcement.

Figure (6) gives the design details of Series 1 girders; figure (7) gives similar particulars of Series 2 girders.

Each of the test girders consisted of two test panels; only one panel was tested at a time. The panel not under test was temporarily stiffened by clamping two stiffeners to its web in order to prevent any distortion occurring on it, while the other panel was being tested. This procedure was repeated with the second panel.

Table 1. Gives the measured loads from these tests and compare them with the predicted values of ultimate shear, using reinforced opening are generally greater than those obtained with unperforated webs.

The loads predicted are seen to be consistently safe and satisfactory. The mean value of, predicted ultimate load / previously experimental ultimate load [4] , for the 6 tests in series 1 (with circular openings) was 0.895 with a standard deviation of 0.037; the corresponding mean value for 10 tests in series 2 with rectangular openings was 0.931 with a standard deviation of 0.055 (see Table 1).

CONCLUSION

The paper presents methods of predicting the ultimate shear of plate girders containing reinforced rectangular and circular openings. The theory accounts for the buckling load of the web, the post-buckling membrane stress developed in the flanges and in the reinforcement. Comparison of result on model girders confirm the validity of the theory.

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Table 1

PREVIOUSE EXPERIMENTAL VALUES OF ULTIMATE LOAD COMPARED WITH PREDECTED VALUES

panel desingation	predicted ultimate load (KN)	Expermental ultimate load [4] (KN)	Predicted load / Expermental load [4]
Series 1 :			
TCP1A	31.8	33.1	* * *
TCP1B	33.5	36.2	0.925
TCP2A	39.1	43.5	0.899
TCP2B	49.6	49.6	0.939
TCP3A	43.1	53	* * *
TCP3B	46	55.8	0.824
TCP4A	54.4	61.8	0.88
TCP4B	68.7	75.9	0.905
Mean value of (Predicted load) /(Expermental load) for 6 tests = 0.895 standard deviation =0.037			
SERIES 2 :			
GP1A	43.2	46.3	* * *
GP1B	43.3	46	0.941
GP2A	48.3	55.5	0.869
GP2B	48.8	55	0.888
GP3A	46.6	46.3	1.007
GP3B	44.2	46.4	0.953
GP4A	44.3	48	0.092
GP4B	43.1	45.5	0.947
TCP5A	34.3	34.3	* * *
TCP5B	39.5	39.5	1.04
TCP6A	33.5	33.5	0.868
TCP6B	33.8	33.8	0.895
Mean value of (Predicted load /expermental load) for 10 tests =0.931 standard deviation = 0.055			

*** These are control tests carried out on pannel without opening. It will be seen that the collepce loads of models having reinforced openings are at least equal to those with unperforated webs.

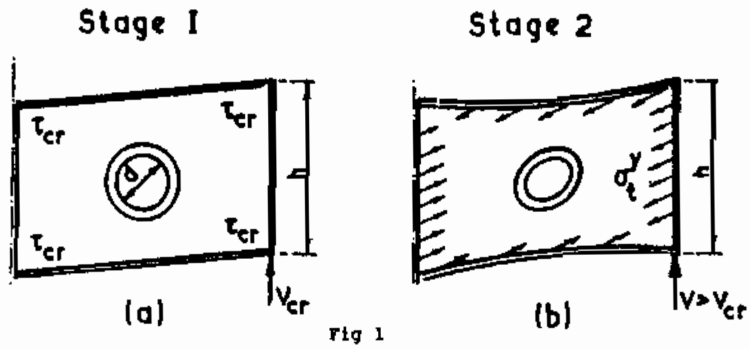


Fig 1

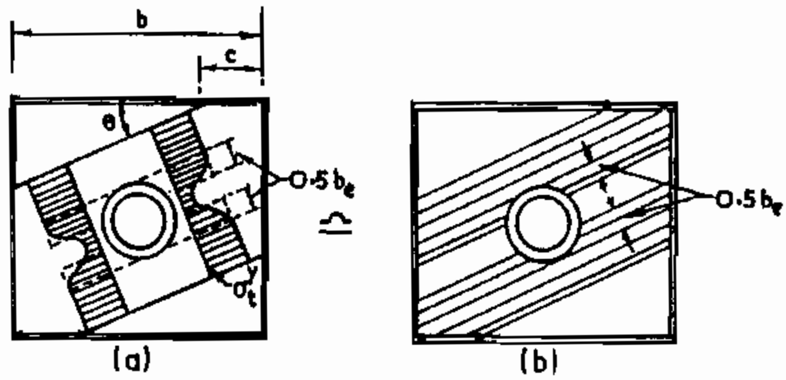
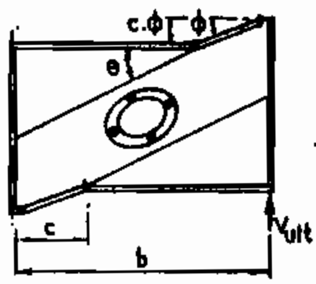


Fig 2



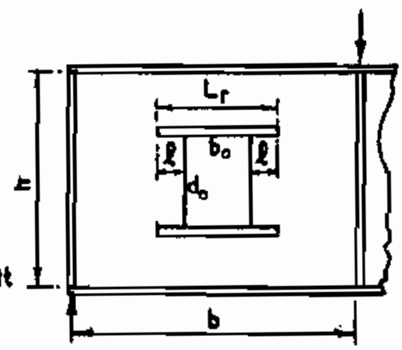


Fig 3 Collapse state

Fig 4 Flat plate reinforcement

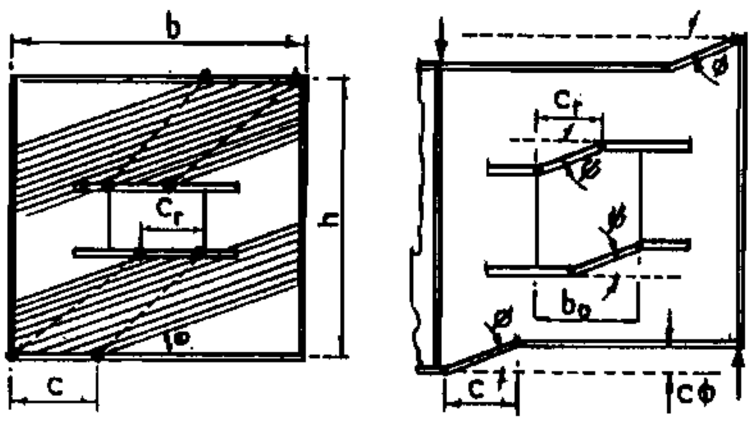


Fig 5

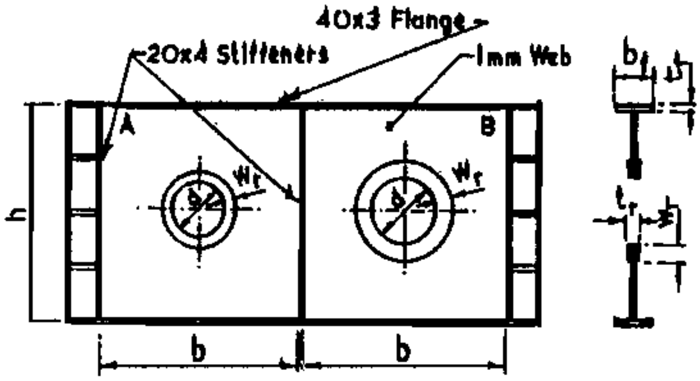


Fig 6 Design details of test specimens - Series 1 [6]

Girder No.	Flange $b_f \times t_f$	Web b x h	CUTOUT IN PANEL A		CUTOUT IN PANEL B	
			Diameter	Reinforcement	Diameter	Reinforcement
TCP 1	40 x 3	375x250	0	-	55	11 x 5
TCP 2	40 x 3	375x250	85	17 x 5	125	25 x 5
TCP 3	40 x 3	360x360	0	-	80	16 x 5
TCP 4	40 x 3	360x360	122	25 x 5	180	37 x 5

Notes: All dimensions are in mm. All panels are made of Grade 43 steel. All webs are cut from single sheet of rolling. All flanges are cut from a single batch of rolling.

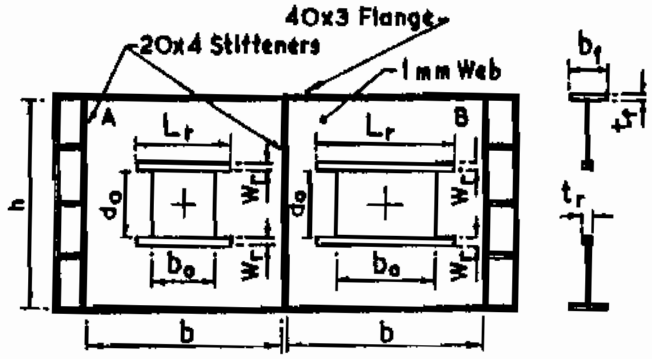


Fig 7 Design details of test specimens - Series 2

Girder No.	Flange $b_f \times t_f$	Web b x h	CUTOUT IN PANEL A		CUTOUT IN PANEL B	
			Size	Reinforcement	Size	Reinforcement
GP 1	40 x 3	300x300	0	-	100x50	18 x 150 x 5
GP 2	40 x 3	300x300	100x150	35 x 260 x 5	100x175	40 x 300 x 5
GP 3	40 x 3	300x300	50x100	21 x 174 x 5	100x100	27 x 174 x 5
GP 4	40 x 3	300x300	150x100	31 x 225 x 5	175x100	34 x 263 x 5
TCP5	40 x 3	450x300	0	-	100x100	26 x 245 x 5
TCP6	40 x 3	450x300	175x100	32 x 260 x 2	250x100	38 x 375 x 5

Notes: As for table under Figure 6.