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Autor(en): **Davies, J.M. / Lawson, R.M.**

Objekttyp: **Article**

Zeitschrift: **IABSE proceedings = Mémoires AIPC = IVBH Abhandlungen**

Band (Jahr): **2 (1978)**

Heft P-16: **Light gauge steel diaphragms with openings**

PDF erstellt am: **08.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-33220

Light Gauge Steel Diaphragms with Openings

Diaphragmes en tôle mince profilée avec des ouvertures

Profilblechscheiben mit Öffnungen

J. M. DAVIES
BSc, PhD, FICE, FIStruct E, CEng
Reader in Civil Engineering
University of Salford, England

R. M. LAWSON
BSc, PhD, ACGI
Ove Arup & Partners
London, England

SUMMARY

In recent years, a great deal of effort has been expended in developing practical methods for the design of light gauge steel diaphragms. However, the important problem of the design of diaphragms containing significant openings has been largely ignored. In this paper, four alternative approaches to the problem are considered and compared and an understanding of the detailed behaviour of a diaphragm in the region of an opening is gained. The study is concluded by the presentation of a complete practical design procedure.

RÉSUMÉ

Un grand effort a été fait ces dernières années pour développer des méthodes pratiques pour le dimensionnement de diaphragmes en tôle mince profilée. Cependant, le problème important du projet de diaphragmes comprenant des ouvertures non négligeables a été laissé de côté. Cette étude considère et compare quatre approches différentes du problème, et conduit à une meilleure compréhension du comportement réel du diaphragme dans la zone d'une ouverture. L'article présente en conclusion une méthode de dimensionnement pratique et complète.

ZUSAMMENFASSUNG

Neuerdings wurde intensiv an der Entwicklung praktischer Methoden zur Berechnung von Profilblechscheiben gearbeitet. Ein wichtiges Problem wurde dabei allerdings zu wenig untersucht: der Entwurf von Scheiben mit grösseren Öffnungen. Die Autoren betrachten vier Lösungsmöglichkeiten und vergleichen sie miteinander; dadurch wird das tatsächliche Verhalten der Scheibe im Bereich einer Öffnung besser verstanden. Abschliessend stellt man ein vollständiges Berechnungsverfahren für die Praxis vor.

1. INTRODUCTION

In recent years a great deal of effort has been expended in various parts of the world in developing accurate and rational methods for the design of light gauge steel diaphragms [1-6] and methods of stressed skin design incorporating diaphragm action are being codified in many countries. Despite this effort, scant attention has been paid to the important problem of the design of diaphragms containing significant openings. As many light gauge steel roof systems contain roof lights this problem is by no means trivial yet the authors are only aware of one reference which provides quantitative information [7] and this is very limited in its treatment.

2. GENERAL

The layout of a typical diaphragm incorporating openings is shown in Fig 1. It is assumed that the diaphragm is constructed using profiled steel sheeting or decking and consequently the deflections are primarily influenced by the shear force and the shear flexibilities of the components [4]. Furthermore, it is now well established [8, 9] that the effective shear modulus of profiled steel sheet is proportional to the length measured parallel to the corrugations so that short lengths of sheet have considerable shear flexibility. By breaking the sheet length into smaller units as well as by removing material, openings cause sharp discontinuities in the shear stiffness and this is reflected in the deflected shape as shown in Fig 1. Purlins with relatively low minor axis bending stiffness tend to be constrained to follow this deflection profile with a consequent significant minor axis bending moment. High local forces in the sheet/purlin fasteners are also induced and the situation may be further complicated by the tendency of light gauge steel purlins to twist.

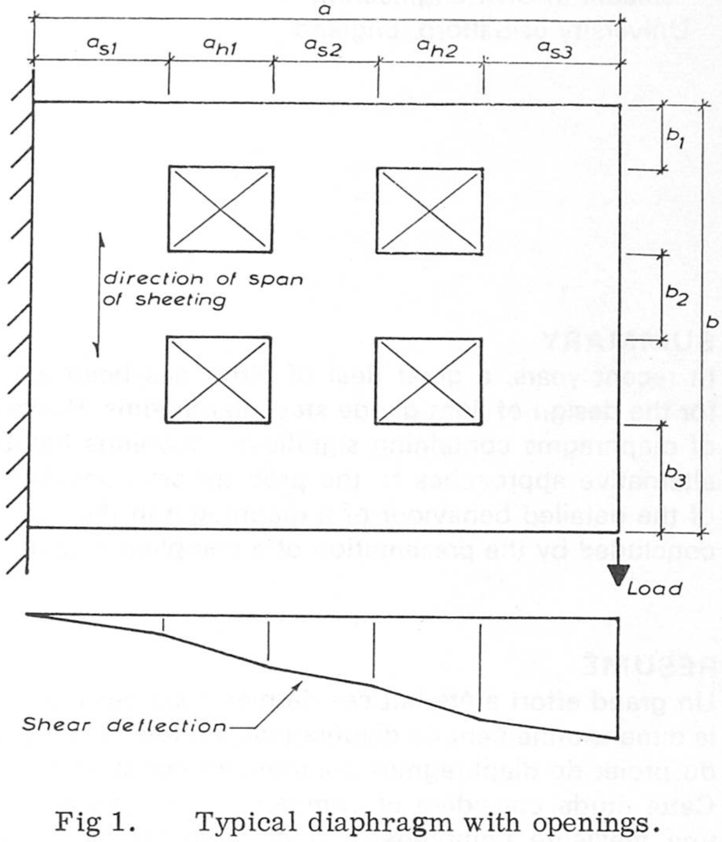

Fig 1. Typical diaphragm with openings.

3. A BASIC APPROACH TO SHEAR FLEXIBILITY

The considerations in the above paragraph suggest a simple approach to the calculation of the shear flexibility of diaphragms incorporating openings. For rectangular diaphragms with no openings it has been shown [4, 6] that the flexibility can be obtained with adequate accuracy as the sum of six component flexibilities, $c_{1.1}$, $c_{1.2}$, etc each of which can be estimated from a simple expression. The term $c_{1.1}$ due to the distortion of the corrugation profile is often the most important and the relevant expression has been recently modified [8,9] to

$$c_{1.1} = \frac{a\,d^{2.5}\,\overline{K}\,f_1}{E t^{2.5}\,b^2} \qquad \text{...... (1)}$$

where
a = width of diaphragm (mm - see Fig 1)
b = depth of diaphragm (mm - see Fig 1)
d = pitch of corrugations (mm)
E = Young's modulus (kN/mm^2)
t = net thickness of sheeting (mm)
$\overline{K}$ = dimensionless constant which is a property of the sheeting profile
f_1 = dimensionless factor allowing for the effect of intermediate purlins

Equation (1) has been shown to be much more accurate than its predecessor [4,6] and is now advocated for practical usage.

Openings cause a significant modification to $c_{1.1}$ together with various other secondary changes. If the performance of the diaphragm is satisfactory it is likely that the secondary changes can be neglected in their influence on flexibility and that an adequate and conservative value can be obtained by modifying $c_{1.1}$ and leaving the other component flexibilities unchanged. A complete design method giving such a satisfactory performance will be presented later.

Using the notation defined in Fig 1 and equation (1) it can be readily shown that, for diaphragms with openings, $c_{1.1}$ calculated in the absence of the openings is modified by the multiplication factor f_h where:

$$f_h = \frac{a_s}{a} + \frac{a_h}{a}\,\frac{b^2}{\sum_i b_i^2} \qquad \text{...... (2)}$$

and where:

$$a_h = \sum_k a_{hk} = \text{sum of widths of openings}$$

$$a_s = \sum_j a_{sj} = a - a_h \qquad \text{...... (3)}$$

This modification factor will be justified in later sections of the paper.

4. TESTING OF DIAPHRAGMS

In establishing design methods for diaphragms containing openings, testing must play an important role. Indeed, certain aspects of behaviour (eg local deformation of the sheeting at the corner of the hole or twisting of the purlin due to large local forces in the sheet/purlin fasteners) are very difficult to quantify and can best be examined experimentally.

As a basis for this present work a series of eight tests was carried out by Dr E Mendelson under the direction of the first author. These tests served to establish the modes of failure and to provide experimental values of both strength and stiffness whereby appropriate analytical approaches could be evaluated. The test arrangement was the conventional cantilever diaphragm shown with a single opening in Fig 2.

The only measurements taken during testing were of the deflection in line with the load together with deflections at other points (not shown in Fig 2) in order that more detailed consideration could be given to displacements in the vicinity of the openings and in order that the results could be corrected for bodily rotation of the complete rig. An alternative arrangement with two openings is shown in Fig 3.

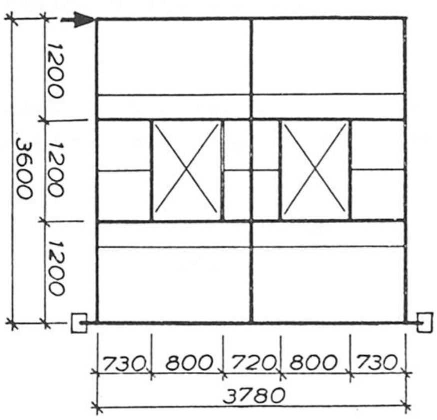

Fig 3. Positions of openings (tests 2 and 7).

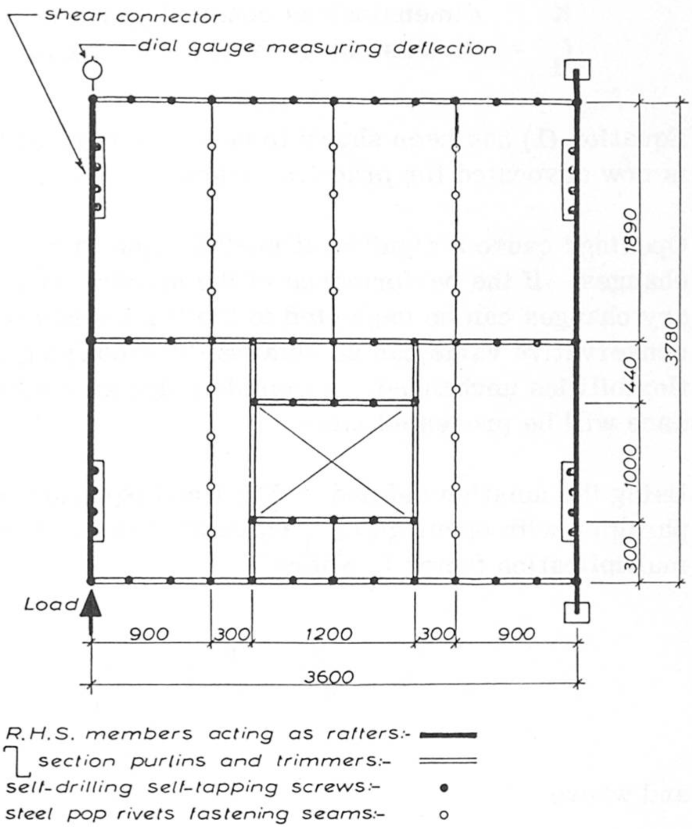

Fig 2. General arrangement of test panel (single opening).

The following additional data applied to all of the tested diaphragms.

Purlins and side trimmers : Z1720 $I_{yy} = 34.53cm^4$

Upper and lower trimmers : Z1420 $I_{yy} = 20.04cm^4$

Fasteners to purlins and trimmers : 1/4 - 14 self-drilling, self-tapping screws with neoprene washers.

Flexibility : $s = 0.18mm/kN$

Ultimate strength : $F_p = 3.77kN$

Seam fasteners : steel blind rivets

Flexibility : s_s = 0.15mm/kN

Ultimate strength : F_s = 1.95kN

The following options were available:

- The number of openings could be varied. Tests were conducted with 0, 1 and 2 openings, the sizes and positions being as shown in Figs 2 and 3.
- The shear connectors (s/c) could be retained (direct shear transfer designated D) or omitted (indirect shear transfer designated I).
- The sheet/purlin (s/p) fasteners could be in every trough of the corrugations (designated E) or alternate troughs (designated A).
- The openings could be fully trimmed as shown (designated F) or trimmed at the top and bottom of the openings only (designated T & B). It may be noted that the latter trimmers are essential in order to restrain the shear distortion of the profiled sheeting.

The arrangement of seam fasteners for plain seams and a seam cut by a single opening is shown in Fig 2. A similar arrangement was used for the panels with two openings. The self-drilling, self-tapping screws fastening the sheet to the trimmers passed through both sheet thicknesses in the central seam so that the total strength of this seam was very nearly the same as that of a plain seam.

In addition to various combinations of the above options, tests were carried out using the two different available profiles shown in Fig 4 and designated ST35 and R15 respectively. A view of the apparatus as set up for Test No 1 is shown in Fig 5. Details and results for the complete test series are summarised in Table 1 the notation being as defined above. Load-deflection curves are given later in Fig 10.

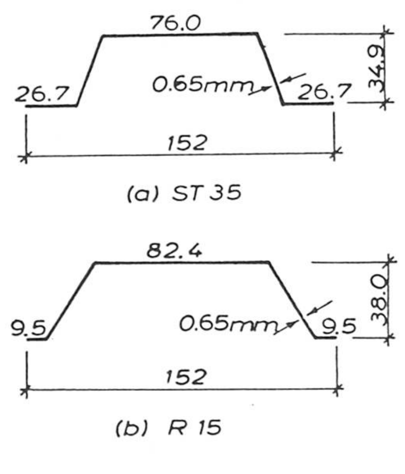

Fig 4. Decking profiles used in tests.

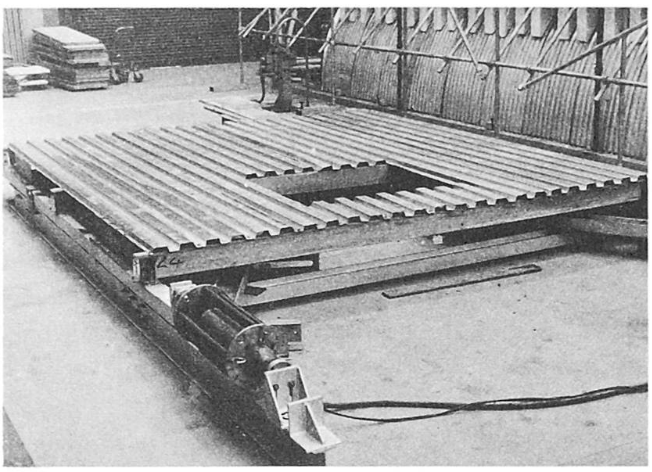

Fig 5. Panel set up for test 1.

Test No.	Sheet type	No. of openings	Trimmers	Sheet/ purlin fasteners	Shear transfer	Failure load (kN)	Flexibility (mm/kN)	Failure mode	Secondary damage	Simple flexibility calculation (mm/kN)	Flexibility calculation using accurate G_{eff}(mm/kN)
1	ST35	1	T& B	A	D	22.0	2.0	central seam above hole	s/p and sheet/ trimmer fasteners in line with hole	1.77	2.01
2	ST35	2	T& B	A	D	15.5	4.3	s/p fasteners in line with holes	sheet distortion at corners of hole. Bending of purlins	4.07	7.56
3	ST35	1	T& B	E	D	31.0	0.40	mainly in central seam above hole	side seams	0.37	0.36
4	ST35	1	F	A	D	24.5	1.8	mainly in central seam above hole	s/p and sheet/ trimmer fasteners in line with hole	1.77	2.01
5	ST35	0	-	A	D	31.6	1.0	central seam	s/c fasteners	1.22	1.22
6	R15	0	-	A	D	32.0	1.4	side seam		1.49	1.49
7	R15	1	F	A	I	13.6	2.4	end s/p fasteners	distortion of purlins at ends	2.22	2.52
8	R15	2	F	A	D	24.0	3.4	side and central seams		5.07	9.43

Table 1. Details and experimental results for complete test series.

In Table 1, the simple flexibility calculation is according to section 3. It may be noted however, that conclusions based on this calculation should be interpreted cautiously as equation (1) is not very accurate for short sheet lengths fastened in alternate troughs. For this reason a second column of calculated flexibilities is also included based on identical reasoning but using an accurate effective shear modulus obtained by finite element analysis [8,9].

The most important conclusions from the test results given in Table 1 are as follows:

- In contrast with the tentative conclusions of reference 7, it is clear that the presence of an opening cutting a seam may weaken that seam even though there is no reduction in the total strength of the fasteners in that seam. This is because the relative flexibilities of the regions of the diaphragm may be so different that there is very little force carried by the more flexible region or regions.

- In several tests, damage to the sheet/purlin fasteners was apparent at load levels below those at which damage would normally have been expected in the absence of the openings. Although bending of the purlins was only significant in one test, purlin bending moments will be increased and must also be examined.

- The simple flexibility calculation given in section 3 is adequate for the cases of a single opening but not for two openings. It is shown later that in tests 2 and 8 much of the shear in the vicinity of the openings was carried by vierendeel action in the purlins and this resulted in unacceptably high minor axis bending moments. Consequently these two tests represent impractical arrangements.

- Significant local distortion of the sheeting was only observed in test 2 for which the situation at failure is shown in Fig 6. This test represents the worst possible combination of parameters (two openings without side trimmers and with sheet/purlin fasteners in alternate troughs only) and may justifiably be considered to represent bad practice.
- It is clear that the internal forces in the region of an opening are complex and that before any simplified design procedures may be established it is necessary to carry out some comprehensive analyses whereby the fastener forces and purlin bending moments may be examined.

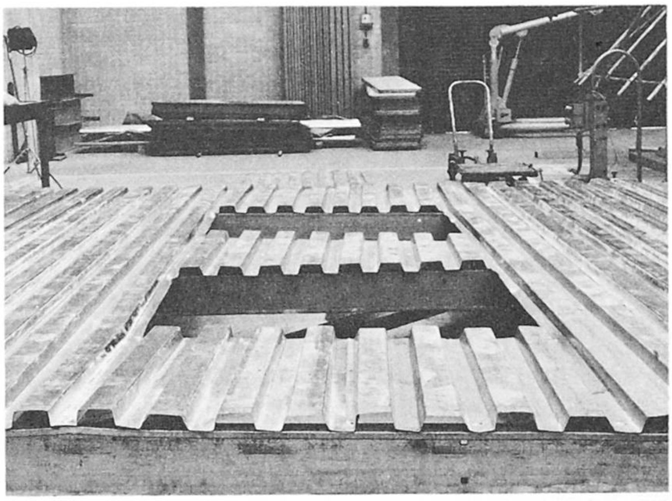

Fig 6. Panel of test 2 at failure.

5. FINITE ELEMENT ANALYSIS OF DIAPHRAGMS

The finite element analysis of complete diaphragms is now well established [5,6] and provides a powerful tool for research and development. It also provides a useful design aid provided that the data can be generated automatically. Unfortunately, it does not appear feasible to develop a data generator for the general case of a diaphragm with one or more openings so that this method does not provide a practicable design office approach. Nevertheless, it is an accurate and reliable method of analysing diaphragms and provides a yardstick whereby other techniques may be assessed.

A finite element simulation appropriate to the tested diaphragms with one opening and sheet/purlin fasteners in alternate corrugations is shown somewhat diagrammatically in Fig 7. The particular trimmer and fastener details shown are appropriate to test 4 but other details can be substituted with only minor modifications to the data. The arrangement of trimmers for test 4 is shown in Fig 8. Of particular note are the connections at the ends of the trimming members which are capable of providing a possibly significant but indeterminate amount of continuity of bending moment. The data for this arrangement allowed meaningful investigations to be made concerning tests 2, 4 and 7. Tests 5 and 6, which fell within the scope of the available data generator, were also analysed. As an alternative simpler analysis was also available, it was not thought necessary to undertake the preparation of data appropriate to tests 2, 3 and 8.

Finite element analyses provide a vast amount of data and it is only possible to present a limited amount of information within the confines of a paper. An appropriate comparison of results will be given in section 7 after an alternative analysis has been described.

6. APPROXIMATE ANALYSIS OF DIAPHRAGMS WITH OPENINGS

It has been shown [10] that light gauge steel diaphragms can be readily analysed using available computer programmes for plane frame analysis. A suitable plane frame analogy for a diaphragm containing a single opening is shown diagrammatically in Fig 9. By suitable manipulation of the member stiffnesses the same arrangement can also be used to analyse a diaphragm with two openings. The following points may be noted in connection with Fig 9.

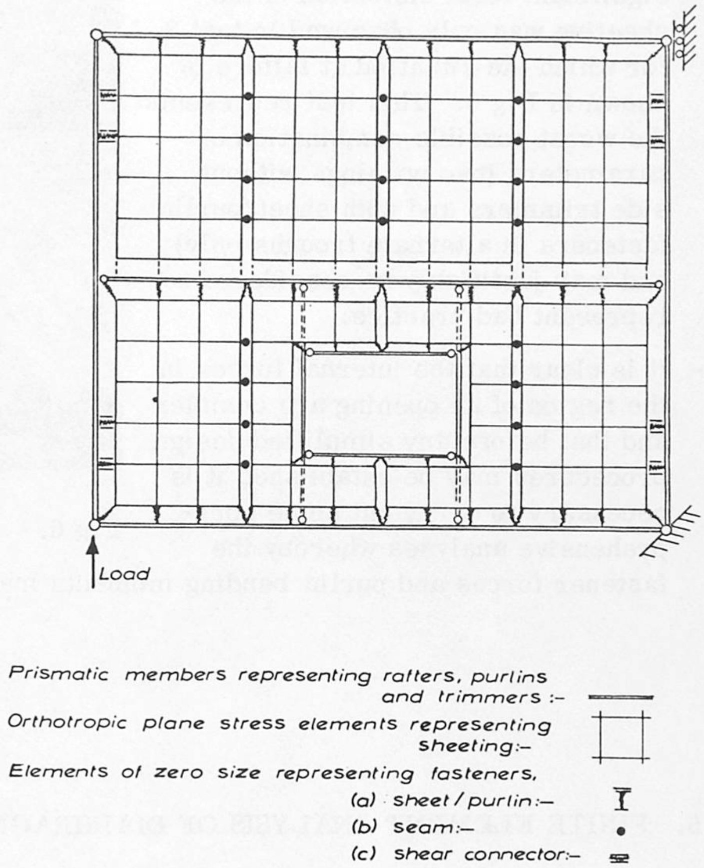

Fig 7. Finite element representation (test 4)

- The joints are permitted to have freedom in the y-direction but are partially restrained so that movement in the x-direction is prevented An alternative procedure is to complete the truss using suitable members of large cross-sectional area.
- In the x-direction dimensions are in accordance with the prototype and sheet/purlin fasteners are represented individually.
- In the y-direction the dimensions are arbitrary and purlins and sheet/purlin fasteners that are subject to similar conditions of internal force and displacement are grouped together.
- The purlins have appropriate minor axis bending stiffness and the remaining members have axial stiffness only. The members shown by heavy lines are sufficiently stiff for their axial strain to be neglected.
- The diagonal members represent the flexibility of profiled steel sheeting and have a cross-sectional area given by:

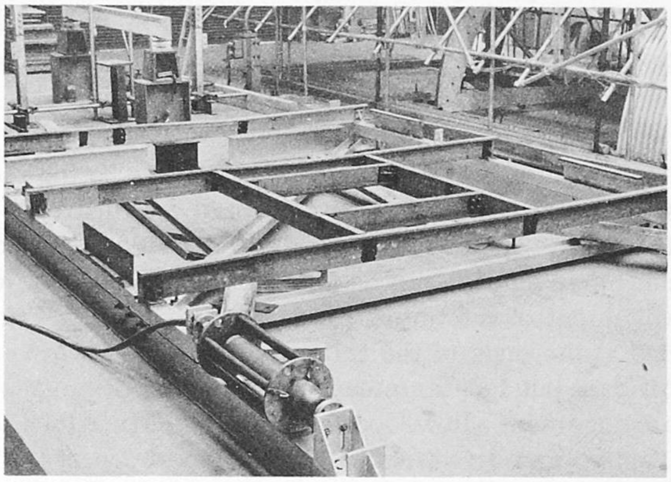

Fig 8. Arrangement of framing and trimmers for test 4.

$$A = \frac{b\,t\,G_{eff}\,l^3}{p\,E\,h^2} \qquad \text{...... (4)}$$

where:

- l = length of the diagonal member
- E = Young's Modulus
- t = net thickness of profiled steel sheet
- G_{eff} = apparent shear modulus of the steel sheet
- b = depth of diaphragm
- p = pitch of sheet/purlin fasteners
- h = depth of the truss assembly representing the sheeting

A suitable value of G_{eff} may be deduced from the theoretical expressions for the shear flexibility of profiled sheets [6,8,9].

- By treating the fasteners as elastic-plastic springs the elastic-plastic behaviour of diaphragms can be investigated. If appropriate, the purlins can also be allowed to develop plastic hinges. This possibility of investigating the elastic-plastic behaviour proves to be of great importance as the redistribution of internal forces is much more significant in diaphragms containing openings than in plain diaphragms. However, the use of a simple bi-linear fastener characteristic underestimates the deflections in the elastic-plastic range as fastener load-deflection curves are highly non-linear.

The success of this approach can be examined in two ways. In the first instance, comparison can be made between the results of finite element and truss analogy results. Successful comparisons of this type were made previously in order to justify the approximate analysis [10]. Further justification can be obtained by direct comparison of experimental results and approximate analysis.

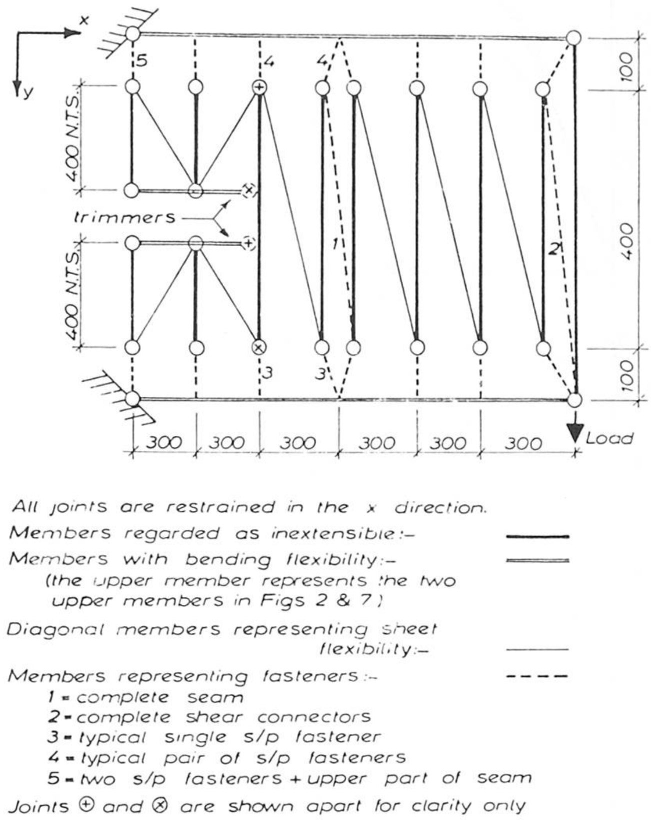

Fig 9. Simulation of a diaphragm with an opening.

7. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

A comprehensive comparison of the significant experimental and theoretical results is given in Table 2. Experimental and theoretical (elastic-plastic) load-deflection curves are compared in Fig 10. In these comparisons two sets of theoretical results are given.

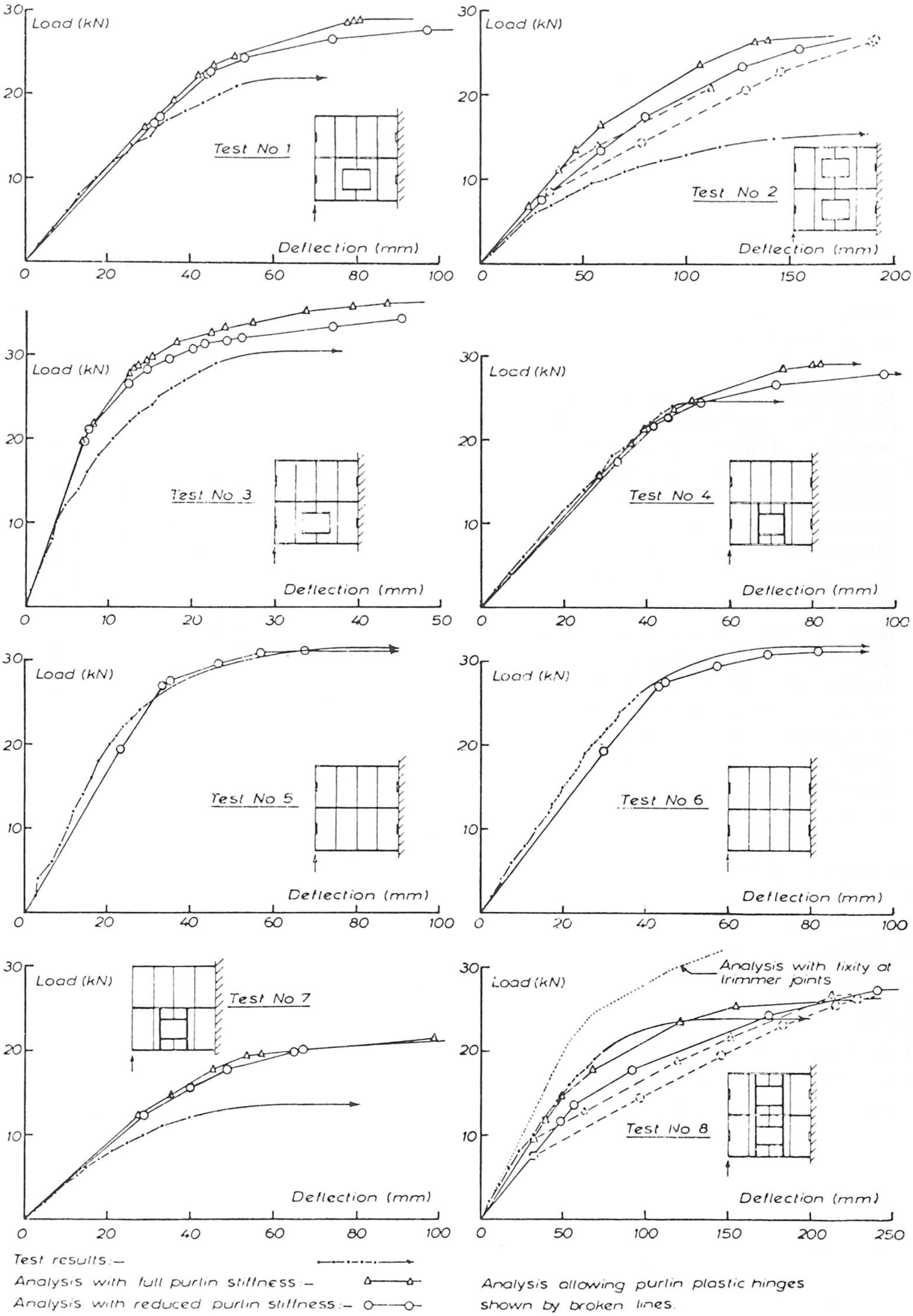

Fig 10. Load-deflection curves for tests.

The upper line of results in Table 2 was obtained using the full minor axis stiffness of the purlins (I_{yy} = 34.53cm^4). The lower line of results uses a reduced stiffness (I_{yy} = 14.20cm^4) which gives approximate consideration to the tendency of the purlins to twist. For tests 5 and 6 which had no openings only one set of results is given as the results were virtually identical. The test results will be discussed with reference to the theoretical results for purlins of reduced stiffness which are considered to be more realistic. The alternative results for purlins of full stiffness are not greatly different and when these are compared with the test results the conclusions are similar.

Experiment			Finite Element Analysis				Approximate (truss analogy) analysis					
Test No.	Flexibility (mm/kN)	Failure load (kN)	Flexibility (mm/kN)	Failure load (kN)	s/p fastener force (kN)	Max purlin B.M(kNmm)	Flexibility (mm/kN)	Failure load (elastic)kN	Failure load elastic - plastic (kN)	s/p fastener force(kN)	Max purlin B.M(kNmm)	Failure mode and subsequent behaviour
1	2.0	22.0	1.99 2.10	21.0 21.3	.192 .165	59.2 39.8	1.82 1.89	21.9 22.2	22.3 22.5	.154 .126	47.5 30.8	Side seam. Upper part of ℄ seam failed at $\frac{24.7}{22.8}$ kN
2	4.3	15.5					3.03 3.80	7.9 7.8	7.9 7.8	.475 .484	143.2 119.1	Sheet/purlin fastener yield. Side seams failed at $\frac{16.4}{17.5}$kN and outer parts of ℄ seam at $\frac{30.7}{30.5}$ kN.
3	0.40	31.0					0.358 0.361	21.9 21.0	21.8 21.0	.0187 .0166	7.3 3.5	Upper part of ℄ seam. Side seam failed at $\frac{28.6}{28.2}$ kN
4	1.8	24.5	1.89 2.01	20.7 21.0	.194 .165	56.1 38.8	1.81 1.88	20.6 21.3	21.1 21.6	.200 .161	52.5 34.4	Side seam. Upper part of ℄ seam failed at $\frac{24.6}{22.7}$ kN
5	1.0	31.6	1.22	27.1	.010	1.0	1.21	27.1	27.0	.010	1.0	Seam failure
6	1.4	32.0	1.49	27.1	.009	1.0	1.49	27.1	27.0	.010	1.0	Seam failure
7	2.4	13.6	2.36 2.49	12.3 12.3	.213 .183	61.4 43.8	2.27 2.36	12.2 12.2	12.2 12.2	.224 .184	58.4 39.7	End shear/purlin fastener (typical of indirect shear transfer)
8	3.4	24.0					3.32 4.14	14.4 13.5	14.6 13.5	.597 .632	154.3 133.8	Side seam. Outer parts of ℄ seam failed at 29.5/28.6 kN but only after s/p faster yields.

Note s/p fastener force in above table refers to the average sheet/purlin fastener force per purlin in line with the edge of the hole.

Table 2. Comparison of experimental and theoretical results.

Taking the tests one at a time, the following points are worthy of note:

7.1 Test 1. The theoretical analysis showed that yield of the two outer seams at a load of 22.5kN would be quickly followed by yield of the part of the central seam above the opening at a load of 22.8kN. This latter eventuality caused a considerable loss of stiffness though the diaphragm was in theory able to accept further load with successive yielding of sheet/purlin fasteners. The initial flexibility was adequately predicted but the test results showed flexibility greater than the theoretical in the later stages of loading. This is typical of most of the results and is an obvious consequence of using a simple bi-linear representation of the highly non-linear fastener load-deflection characteristic.

The experimental failure of the upper part of the central seam at a load of 22.0kN is in reasonable agreement with the theoretical predictions though it is significant that no distress to the side seams was observed.

7.2 Test 2. This test represents an extremely severe case in which the theoretical analysis predicted yield of the highly stressed sheet/purlin fasteners in line with the sides of the openings at a load of 7.8kN followed by yield of the two outer seams at a load of 17.5kN. The elastic-plastic analysis showed a progressive increase of flexibility as successive fasteners yielded but no clearly defined failure. In an alternative analysis allowing plastic hinge action in the purlins, the purlins yielded at a load of 8.7kN and this caused a further sudden increase in flexibility as shown by the broken line in Fig 10.

The initial flexibility of the test diaphragm was adequately predicted but the test diaphragm deteriorated rapidly after the yield of the critical sheet/purlin fasteners and failed at a load of 15.5kN due to severe deformation around the hole (Fig 6). Though interesting from the theoretical point of view, this diaphragm must be considered to be unsatisfactory from the practical point of view.

7.3 Test 3. This test was the only test on a diaphragm in which the sheeting was fastened to the purlins through every trough of the corrugations. As fastening in every corrugation reduces the shear flexibility of the sheeting, and hence the discontinuity of shear deflection at the edge of the hole, by an order of magnitude it must improve the performance of the diaphragm by an considerable amount. This improvement is reflected in both the experimental and theoretical load-deflection curves.

The upper part of the central seam was predicted to yield at a load of 21.0kN but at this stage the region of sheeting below the opening was almost unstressed. There was no appreciable increase in flexibility until the outer seams also yielded at a load of 28.2kN. Thereafter, the diaphragm was capable of accepting further load but with significantly increased flexibility.

The test results showed a failure load of 31.0kN with failure taking place in the upper part of the central seam but with the outer seams close to failure. The theoretical ultimate load of the corresponding panel without any opening according to reference 6 was 29.7kN.

7.4 Test 4. This test was a repeat of test 1 but with the opening trimmed on all four sides. Apart from a small decrease in flexibility the theoretical load-deflection curve was almost identical to that of the first test. The test results confirmed the small reduction in flexibility and also showed an increase in failure load from 22.0kN to 24.5kN. The experimental failure load could have been enhanced by some bending moments passing through the trimmer joints. These were assumed to be pinned for the purposes of analysis.

7.5 Tests 5 and 6. These tests were carried out for comparison purposes on panels without openings. The theoretical failure loads according to reference 6 were both 27.5kN and this value compares well with the alternative theoretical values given in Table 2. The theoretical elastic-plastic load deflection curves shown significant redistribution of load before failure in a collapse "mechanism" at a load of 31.2kN. The observed failure loads of 31.6kN and 32.0kN respectively suggest that this redistribution may have taken place.

7.6 Test 7. This test differed from the other seven tests in that the shear connectors were omitted and therefore the applied shear force passed from the rafters into the decking through the purlin/rafter connections and sheet/purlin fasteners. Although the test panel contained an opening the results are dominated by the high forces in the outermost sheet/purlin fasteners. Failure of the test panel took place at a load of 13.6kN when the sheet material tore at these fasteners accompanied by twisting of the ends of the purlins. A simple calculation for this mode of failure has been given and is supported by finite element analysis and test results [6,11]. The failure load calculated according to this calculation is 12.8kN which is in reasonable agreement with both the theoretical and observed failure loads. Detailed analysis confirms that the critical end sheet/purlin fastener forces are unaffected by the opening in the diagram.

7.7 Test 8. For this test, the panel incorporated two fully trimmed openings and the test results were evidently strongly influenced by the stiffness of the trimmer system. This is the only test in which the experimental load-deflection curve lay above the theoretical in the non-linear region and this result could only be attributable to the stiffness of the joints between the trimmer members. Accordingly, a further analysis was performed in which the trimmer joints were prevented from rotating. The results are shown as the dotted line in Fig 10. The initial flexibility was reduced from 4.14mm/kN to 2.42mm/kN and equally great reductions of flexibility were found at later stages of loading.

As the test result lay roughly between the two alternative theoretical analyses the above supposition appears proven. The analysis with rigid trimmer joints revealed outer seam yield at 21.0kN followed by yield of part of the central seam at 24.9kN. These figures are in reasonable agreement with the experimentally observed failure of the side and central seams at a load of 24.0kN.

This test utilised a very similar arrangement to that of test 2 though with the addition of the side trimmers. Although these trimmers reduce the local high fastener forces they do not reduce the purlin minor axis bending moments and an alternative analysis allowing purlin plastic hinges, again showed purlin yield with an accompanying increase in flexibility at the low load of 7.4kN. Even though the complete trimmer system helps to contain the high fastener forces and increased the failure load from 15.5kN in test 2 to 24.0kN in test 8, bending in the purlins means that this still represents an unsatisfactory arrangement.

8. CONCLUSIONS FROM TEST RESULTS AND ANALYSIS

- In comparison with finite element analysis, the approximate truss analogy gives a perfectly adequate representation of the elastic response of the diaphragms and the added complications of a full finite element analysis are unnecessary.
- Redistribution of internal forces due to fastener yield can be significant. In particular initial high forces at the seams adjacent to the openings dissipate quickly and it is unnecessary to consider these in detailed design.
- High forces may occur in the sheet/purlin fasteners adjacent to the sides of openings and these can be large enough to cause premature failure. However, if all four sides of the openings are trimmed and if fasteners between the side trimmers and the sheets are incorporated these fastener forces are much reduced. The avoidance of unduly high local sheet/purlin fastener forces must be considered to be essential.
- Excessive bending of the purlins about their minor axis does not appear to cause any reduction in the strength of the diaphragm and early purlin yield may indeed be beneficial in reducing local fastener forces. However, severe minor axis bending of the purlins is likely to be accompanied by excessive twisting and should be avoided.

- The tests described in this paper were severe cases in which it was expected that the openings would cause a significant reduction in both the strength and stiffness of the diaphragms. Tests 2 and 8 considered a situation which made the region of the openings so flexible that in the initial elastic phase most of the shear was carried by the purlins. Nevertheless in test 8 the failure load was only reduced by 13% below the theoretical failure load of the same diaphragm without openings (27.5kN). A similar result was obtained for test 4 although, conversely, the corresponding tests without side trimmers (tests 2 and 1 respectively) performed less satisfactorily. It follows that diaphragms with large fully trimmed openings are robust and even with sheet/purlin fasteners in alternate corrugations are only subject to small decreases in failure load. When, as will usually be the case, the fasteners are in every corrugation the situation is even more favourable (test 3). Because of this robust nature, it appears possible to rely on a relatively simple analysis provided that an adequate estimate can be made of the following properties:-

(a) (increased) flexibility
(b) (reduced) ultimate load
(c) local high sheet/purlin fastener force
(d) local high purlin minor axis bending moment.

A simplified analysis for the two latter properties will now be described.

9. DESIGN EQUATIONS FOR DIAPHRAGMS WITH OPENINGS

Notwithstanding the success of the approximate (truss analogy) method of analysis which brings the problem within the capability of the average design office it remains desirable to provide a more readily usable approximate approach for practical arrangements of openings. In this approximate analysis the fasteners are treated as a continuum and it is assumed that all of the purlins behave identically. The differential equations which govern the behaviour of the purlins and fasteners in the vicinity of the openings can then be determined and solved for the appropriate boundary conditions.

This approach is considered to be valid provided that the following conditions are satisfied:-

- Openings occur singly or in bands running parallel to the corrugations.
- The opening or band of openings has a total depth which is less than one third of the depth of the diaphragm.
- Openings are spaced so that in a direction normal to the corrugations the clear distance between openings or bands of openings is at least equal to the width of the largest adjacent opening.

The above conditions may be considered to represent good practice and may be considered to be necessary even if it is proposed to carry out a more detailed analysis in accordance with sections 5 or 6. It should be observed that of the cases tested, tests 2 and 8 with two openings violate the second condition.

In deriving the design expressions which follow, two different cases were considered, as shown in Fig 11. In the first case (a) a single section of high flexibility c_h caused by an opening or band of openings occurs within an infinite length of flexibility c_s. In the second case (b), flexible sections occur periodically at regular intervals.

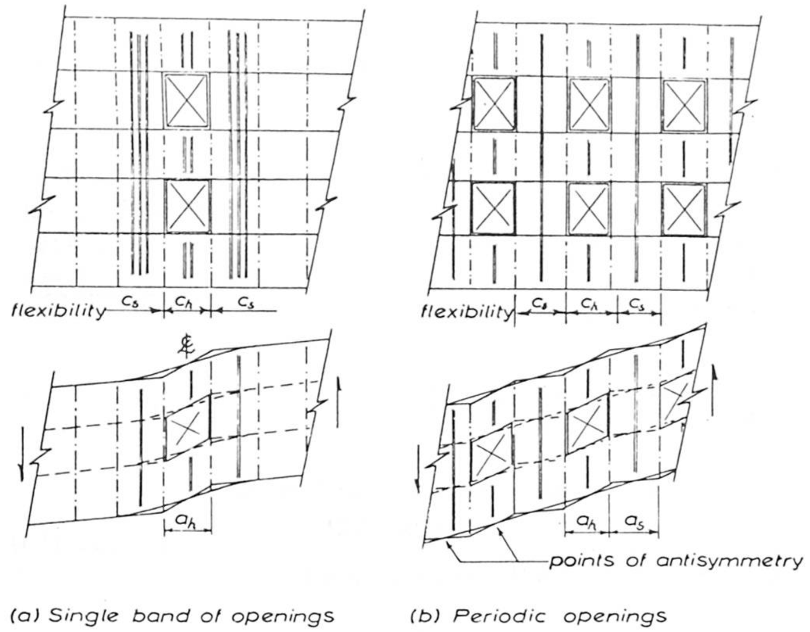

Fig 11. Cases for approximate analysis.

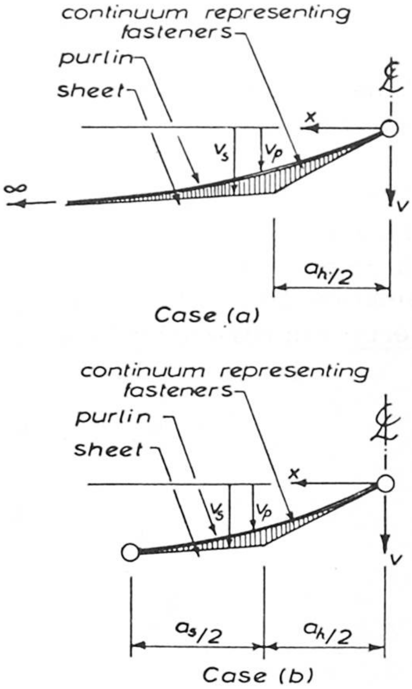

Fig 12. Displacement components.

For both cases, the differential equations governing the behaviour of the assembly are identical though the boundary conditions differ. The two situations are shown in Fig 12 and, using the notation defined in that figure, the behaviour of the three constituent elements is governed by the following equations:-

purlin $$EI \frac{d^4 v_p}{dx^4} = q \qquad \ldots\ldots (5)$$

fastener $$\frac{1}{sp}(v_s - v_p) = q \qquad \ldots\ldots (6)$$

sheet $$\frac{1}{c}\frac{d^2 v_s}{dx^2} = n_p q \qquad \ldots\ldots (7)$$

where:

EI	=	flexural rigidity of a single purlin about its minor axis
n_p	=	number of purlins
s	=	flexibility of an individual fastener
p	=	pitch of fasteners
q	=	equivalent fastener force per unit length
v_s, v_p	=	displacements of sheeting and purlin respectively in y direction

It then follows that the required differential equation for purlin behaviour is:-

$$sp \frac{d^6 v_p}{dx^6} - c n_p \frac{d^4 v_p}{dx^4} + \frac{1}{EI} \frac{d^2 v_p}{dx^2} = 0 \qquad \ldots\ldots (8)$$

This equation applies to both sections of purlin provided that the appropriate c_s or c_h is substituted for c.

The simultaneous solution of this equation for the two sheet flexibilities with the appropriate boundary conditions is not trivial and an appropriate numerical procedure is given in reference 12. However, it is found that when realistic values are substituted into this solution the results for the two cases are similar and the required values per unit shear force can reasonably be approximated by the following equations:

$$M_{max} = 0.007\,(c_h - c_s)\,I^{3/4} \text{ kNmm/kN} \qquad \ldots\ldots (9)$$

$$F_a = 0.015\,(c_h - c_s)\,I^{1/4} \text{ kN/kN (alternate trough fastening)}$$

$$F_e = 0.010\,(c_h - c_s)\,I^{1/4} \text{ kN/kN (every trough fastening)} \qquad \ldots\ldots (10)$$

where I is the second moment of area of the purlin about its minor axis and c_h and c_s are the sheet flexibilities as defined in Fig 11 in units of mm/kN/m length.

These formulae have the safe property of giving reasonably accurate values in the practical range of flexibility difference ($c_h - c_s < 0.5$mm/kN/m) but overestimating the forces and moments with more flexible arrangements. As periodic openings usually give the worst case, equations (9) and (10) have been subject to a check against a finite element analysis of a panel containing two openings of 2m width spaced 2m apart. Table 3 gives a summary of the results.

Data		Formulae			Finite Element Results		
I (mm^4)	$c_h - c_s$ (mm/kN/m)	M_{max} (kNmm)	F_a (kN)	F_e (kN)	M_{max} (kNmm)	F_a (kN)	F_e (kN)
5 x 10^5	0.729	94	0.29	0.19	63	0.18	0.15
10^5	0.729	28	0.19	0.13	29	0.17	0.13
5 x 10^5	0.450	58	0.18		42	0.13	
5 x 10^5	0.106	14	0.04		14	0.05	
5 x 10^5	0.059	7.6		0.02	7.3		0.03

Note: Values in the above table are per kN shear force.

Table 3. Comparison of results for periodic openings.

Equations (9) and (10) consequently represent a safe and adequate approach to the prediction of the maximum minor axis bending moment and the maximum fastener force in the region of an opening or openings. It is therefore now possible to give a complete design procedure.

10. DESIGN PROCEDURE FOR DIAPHRAGMS WITH OPENINGS

This design procedure is intended to give safe and sufficiently accurate design values for diaphragms of reasonable proportions. Unreasonable arrangements will be quickly revealed as they will give rise to high local forces.

As a general rule, when diaphragms contain openings of significant size, the sheeting should be fastened to the supporting structure through every trough of the corrugations unless the diaphragm is only lightly loaded. Furthermore, it should be considered normal good practice to trim large openings on all four sides and to carry the side trimmers back to the adjacent purlins or other supporting members.

The approach arises initially out of a consideration of Fig 1 :-

- Calculate the ultimate strength Q_{ult} and flexibility c of the diaphragm according to references 6 and 9, ignoring the effect of the opening(s).
- Modify the $c_{1.1}$ component of flexibility according to equation (2) and substitute this into the flexibility calculation to give an estimate of the flexibility of the diaphragm with opening(s).
- Assume that the calculated ultimate shear force Q_{ult} divides itself between the regions above and below the openings according to the relative stiffness of the sheeting. Thus, for a given region (j)

$$Q_j = \frac{c_h}{c_j} Q_{ult} = \frac{b_j^2}{\sum_i b_i^2} Q_{ult} \qquad \ldots\ldots (11)$$

where :

$$c_j = \frac{a\, d^{2.5}\, \overline{K}}{E\, t^{2.5}\, b_j^2} \qquad \ldots\ldots (12)$$

and $\sum_i b_i^2$ is taken over the sheeted regions within the width a_h of the band of openings.

Check that in any seams cut by openings, each region j has sufficient strength to accommodate the calculated shear force Q_j. For this purpose the strength of a region of a seam may be conservatively taken to be:-

$$Q_{j.ult} = n_{pj} F_p + n_{sj} F_s + n_{tj} F_t \qquad \ldots\ldots (13)$$

where, within the region considered:

n_{pj} = number of sheet/purlin fasteners through both sheets
n_{sj} = number of seam fasteners
n_{tj} = number of trimmer fasteners through both sheets
F_p = strength of an individual sheet/purlin fastener
F_s = strength of an individual seam fastener
F_t = strength of an individual sheet/trimmer fastener

If, in any region, $Q_{j.ult} < Q_j$, Q_{ult} should be reduced by multiplying by the smallest value of $Q_{j.ult}/Q_j$ found for the seam considered.

- Establish the sheet flexibility properties in the vicinity of the openings using equation(1)

Thus :

$$c_s = \frac{1000 d^{2.5} \overline{K} f_1}{E\, t^{2.5}\, b^2} \qquad (14)$$

$$c_h = \frac{1000 d^{2.5} \overline{K}}{E t^{2.5} \sum_i b_i^2} \qquad (15)$$

where c_s and c_h are calculated for a = 1000 mm.

- Check the maximum purlin minor axis bending moment according to equation (9). This gives an upper bound to the maximum purlin bending stress as twisting is ignored. A more realistic value may be obtained by using the minor axis second moment of area obtained when the contribution of the bottom flange is neglected. At the calculated ultimate load of the panel the stress should be within the elastic range. Violation of this condition must be taken as an indication that the diaphragm is too flexible in the vicinity of the hole.

- Check the maximum sheet/purlin fastener force according to equation (10). Equation (10) gives the maximum force per purlin per unit shear force in line with the edge of an opening. The total force may be assumed to be taken by the sheet/purlin fasteners together with any fasteners to the side trimmers. Thus for satisfactory performance:

$$n_p F_p + n_t F_t \geqslant Q_{ult}\, n_p \begin{bmatrix} F_a & \\ & \text{as appropriate} \\ F_e & \end{bmatrix} \qquad (16)$$

where n_t is the number of fasteners to trimmers at or in line with one side of the opening or line of openings under consideration. If this condition is violated, extra sheet/trimmer fasteners may be inserted.

The application of the above procedure to the relevant tested diaphragms is given in Table 4.

Test Results			Design Calculations							
Test No	Flexibility (mm/kN)	Failure (kN)	Basic Q_{ult}(kN) (Ref 6)	Basic c (mm/kN) (Eqn 1)	Modified c(mm/kN) (Eqn 2)	Modified Q_{ult}(kN) (Eqn 13)	$c_h - c_s$ (mm/kN/m)	M_{max} (kN mm /kN)	F_e or F_a (kN/kN)	Design Load (kN)
1	2.0	22.0	27.5	1.22	1.77	19.5	0.4553	45.4 23.3	0.166 0.133	19.5
2	4.3	15.5	27.5	1.22	4.07	22.8	2.375	236.8 121.6	0.864 0.692	4.4 5.5
3	0.40	31.0	29.7	0.28	0.37	19.6	0.0597	6.0 3.1	0.0145 0.0116	19.6
4	1.8	24.5	27.5	1.22	1.77	29.5	0.4553	45.4 23.3	0.166 0.133	19.5
8	3.4	24.0	27.5	1.50	5.07	22.8	2.983	297.4 152.7	1.085 0.868	3.5 4.3

Note the upper figures are for full purlin stiffness and the lower figures for reduced stiffness

Table 4. Application of the design procedure to tested diaphragms.

In connection with table 4, the following points may be noted:-

- The calculations have been carried out in accordance with the expressions given above. These are not very accurate for the unrealistically short sheet lengths and alternate trough fastenings used in the test diaphragms. The results given in Table 4 cannot therefore strictly be compared with the corresponding values in Table 2 which were obtained using accurate values for the effective shear modulus G_{eff}. Nevertheless, the results given are considered accurate enough for all practical purposes and this objection would not apply to diaphragms of more realistic depth used in practical situations.
- The diaphragms used in tests 2 and 8 are clearly ruled out on the basis of the high purlin bending moments. In fact the purlins are carrying most of the shear in the region of the openings and the flexibility calculation given above is not valid.
- The diaphragms used in test 3 and 4 are completely satisfactory as far as the design procedure is concerned and the design strengths could be raised to those of the corresponding diaphragms without openings simply by strengthening the seam above the opening.
- For the diaphragm used in test 1 the design procedure also reveals a low strength with respect to the sheet/purlin fasteners in line with the edge of the opening.

CONCLUSIONS

The paper includes a detailed investigation of the behaviour of light gauge steel shear diaphragms incorporating significant openings. It includes the results of tests, finite element analysis and two quite separate approximate analyses. Each of these four approaches gives different and relevant information. The paper concludes by describing a simple and practical design procedure.

ACKNOWLEDGEMENT

The authors would like to express their appreciation for the practical help and encouragement in this work given by Professor E R Bryan and the staff of the Civil Engineering Department at the University of Salford. In particular they are grateful to Dr E Mendelson for carrying out the tests described in this paper.

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