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The Design of Cold Rolled Z-Purlins

Construction de profilés en Z laminés à froid

Die Konstruktion kaltgewalzter Z-Dachstuhlpfetten

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1. Introduction

The design approach to mass produced steel structures, and particularly to mass produced components, may be very different from the approach used in the design of individual structures. With mass produced structures it may well be possible to base the design assumptions on the observed behaviour of members and joints, and to modify the arrangement and details in the light of this behaviour. Such a procedure would rarely be economic in the case of an individually designed structure.

The paper describes how the above approach was used in the design of the cold rolled structural section most widely used in Great Britain, the zed purlin (Fig 1). The work described was undertaken for Metal Trim Ltd in the development of a new range of sections.

Fig 1 Zed Purlins in Practice

2. Preliminary Survey

Before any design work was commenced, a survey of requirements was undertaken by sending questionnaires to a number of leading structural firms. These questionnaires asked for the following information on steel framed buildings erected in recent years:- date, span, frame spacing, roof pitch, purlin type and spacing, and type of roofing. From the replies received it was found that by far the most common frame spacing was 20 feet, followed by spacings of 15 feet and 25 feet. The most common roofing material was asbestos cement, with purlins at 4ft 6in centres. For purlins up to about 20ft span, the purlins were continuous over two spans, but above this span, the purlins were of single span. The most common roof pitch for portal frames was 16 - 19 degrees, but a significant number of buildings had pitches of less than 7 degrees.

From an analysis of the information received it was apparent that any new range of zed purlins must centre around a few popular spans and loadings. For instance, one design must be based on a 20ft span with asbestos cement sheets on purlins at 4ft 6in centres. By this means, the greatest economy would be made in the greatest number of cases.

In addition to giving information on existing buildings, the replies to the questionnaires indicated trends in building dimensions. For instance, the most recent buildings tended to have larger spans, greater frame centres and shallower roof pitches than buildings put up a number of years ago. It was therefore apparent that any new range of zed purlins should cater for these trends and possibly not include the smaller sections in the existing range.

Although it is not possible in a paper of this length to enumerate all the factors which played a part in the consideration of the new range of zed purlins, it is hoped that enough information is given to show the sort of approach which was used.

3. Design Approach

The empirical expression given in the British Standard for the design of zed purlins is that the section modulus (in inch units) shall not be less than $WL/115$ where W is the load on the purlin in tons and L is the span of the purlin in inches. There are also requirements governing the shape of the section. No mention is made of end fixity requirements, although it is common practice to use sleeves between adjoining spans.

In any new design approach it was considered vital to take into account the following factors:-

(1) the most economic profile for the section
(2) the most economic and efficient purlin sleeve and purlin/rafter connection
(3) the actual strength of the steel used.

Item (1) could be determined from theoretical considerations and from a knowledge of the rolling process, but items (2) and (3) could only be obtained from tests. Using the information contained in items (1), (2) and (3), it should be possible to deduce the optimum design for a zed purlin system. In fact, this was the procedure which was adopted.

4. Section Profile

Without any preconceived ideas, various section profiles were considered and rejected one by one until only the nesting zed purlin was left. This section gave the most economic use of material and had the advantage that the same section could be used for the sleeves. The sizes of the flange lips were adjusted (Fig 2) so that the neutral axis of the section should be at mid height and the section modulus as great as possible.

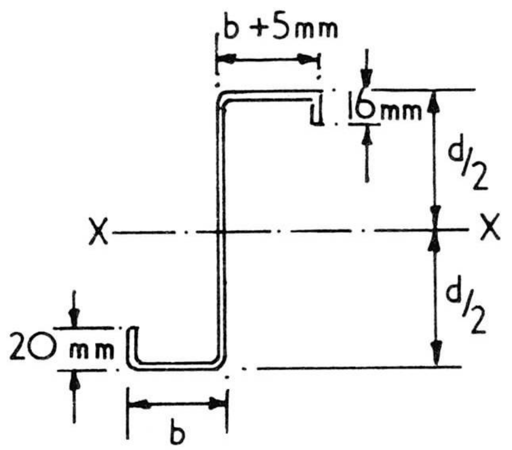

Fig 2 Profile of Zed Purlin

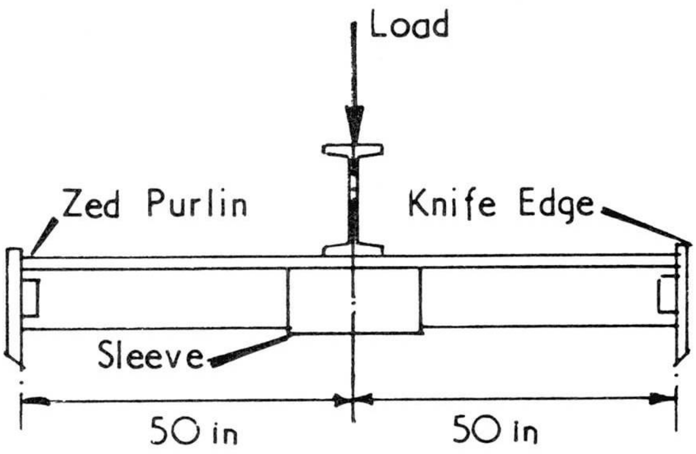

Fig 3 Experimental Arrangement

5. Purlin Sleeve

In order to test various purlin sleeves and purlin/rafter connections, the experimental arrangement shown in Fig 3 was set up using an existing type 7in x 2in x 14 gauge zed purlin. The assembly was put in a testing machine and load-deflection readings taken. Tests were carried out on unjointed purlins (Fig 4) and on twelve different types of bolted sleeves. Fig 5 shows an unsatisfactory detail, and Fig 6 shows a satisfactory arrangement, in fact the one finally adopted. For the section tested it was found that a lipped sleeve 18in long, with 6 - 5/8in black bolts gave the joint with the optimum efficiency and economy.

From Fig 7, it is seen that the deflection of the joint under an applied central moment M may be obtained by subtracting the deflections due to flexure of the unjointed zed from the total deflection of the jointed zed. Hence the moment-rotation curve for the joint (Fig 8) may be derived. In fact, $\theta = 0.403 \times 10^{-3} M$ radians.

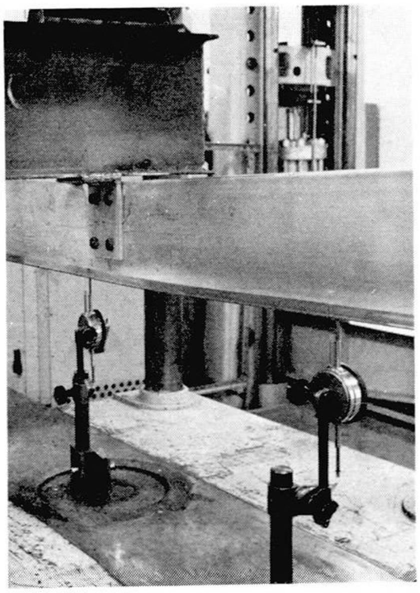

Fig 4

Tests on Unjointed Purlin

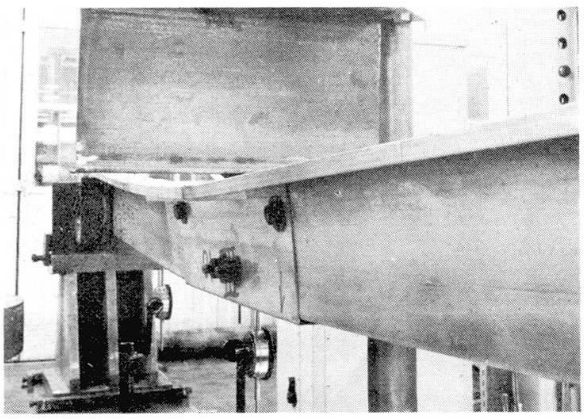

Fig 5

Unsatisfactory Detail

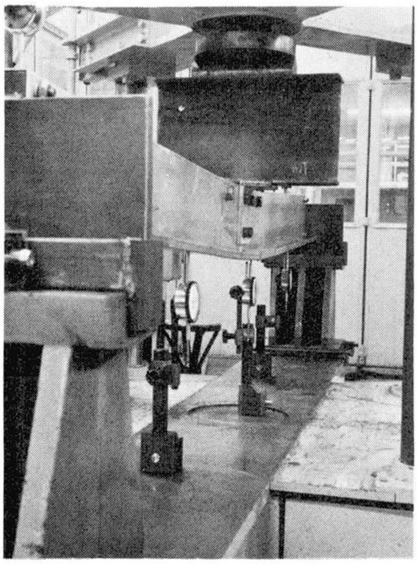

Fig 6

Satisfactory Sleeve Joint

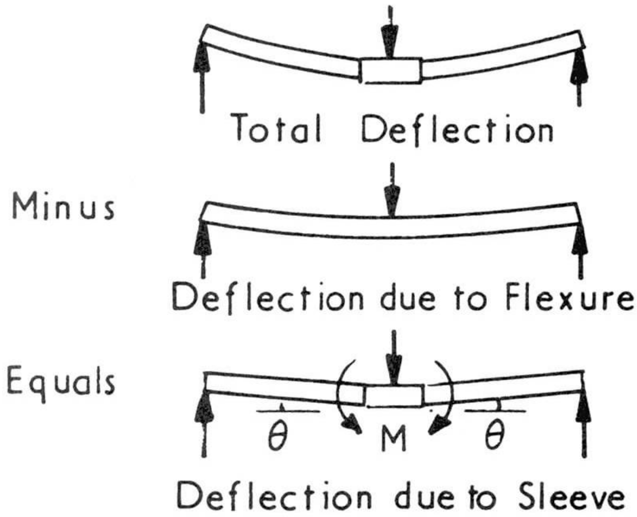

Fig 7

Determination of Sleeve Rotation

6. Material Strength

From the bending test on the unjointed purlin (Fig 4) the yield moment was 38.0 ton in and the section modulus was 2.0in^3, giving a yield stress of 19.0 ton/in^2. This compared with a lowest yield stress of 17.2 ton/in^2 obtained from tensile coupon tests and a guaranteed tensile yield stress of 17.0 ton/in^2 from the manufacturers of the steel strip.

If the permissible working stress is taken as 0.65 times the yield stress, as specified in the British Standard, the nominal design stress is 0.65 x 17 = 11.0 ton/in^2, but the bending stress in the unjointed purlin over the support may be taken as 0.65 x 19 = 12.4 ton/in^2.

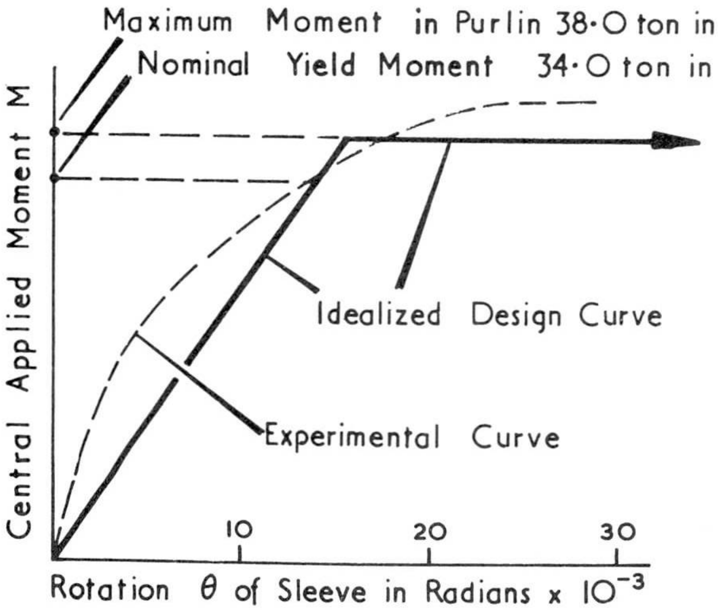

Fig 8 Moment-Rotation Curve for Sleeve Joint

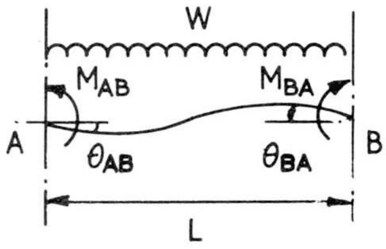

Fig 9

Slope-Deflection Nomenclature

7. Bending Moment Analysis

The analysis of the purlin was carried out by slope-deflection, using the actual moment-rotation relationship for the sleeve. For a 7in x 2in x 14g zed ($E = 13000$ ton/in^2, $I = 7.00$in^4) a 20ft span was normal so $L/6EI = 0.44 \times 10^{-3}$ in ton in units.

For a uniformly distributed load of W on span L the end moments and rotations are given by the following expressions:-

From Fig 9, $\theta_{AB} = -0.44 \times 10^{-3}\left(2M_A + M_B - \frac{WL}{4}\right)$ ...... (1)

From Fig 8, $\theta_{AB} = 0.403 \times 10^{-3} M_A$ ...... (2)

From Fig 9, $\theta_{BA} = 0.44 \times 10^{-3}\left(M_A + 2M_B - \frac{WL}{4}\right)$ ...... (3)

From Fig 8, $\theta_{BA} = -0.403 \times 10^{-3} M_B$ ...... (4)

These expressions were used to determine the maximum moments in the single span and double span purlins shown in Fig 10. As indicated in the figure, there are four cases to consider.

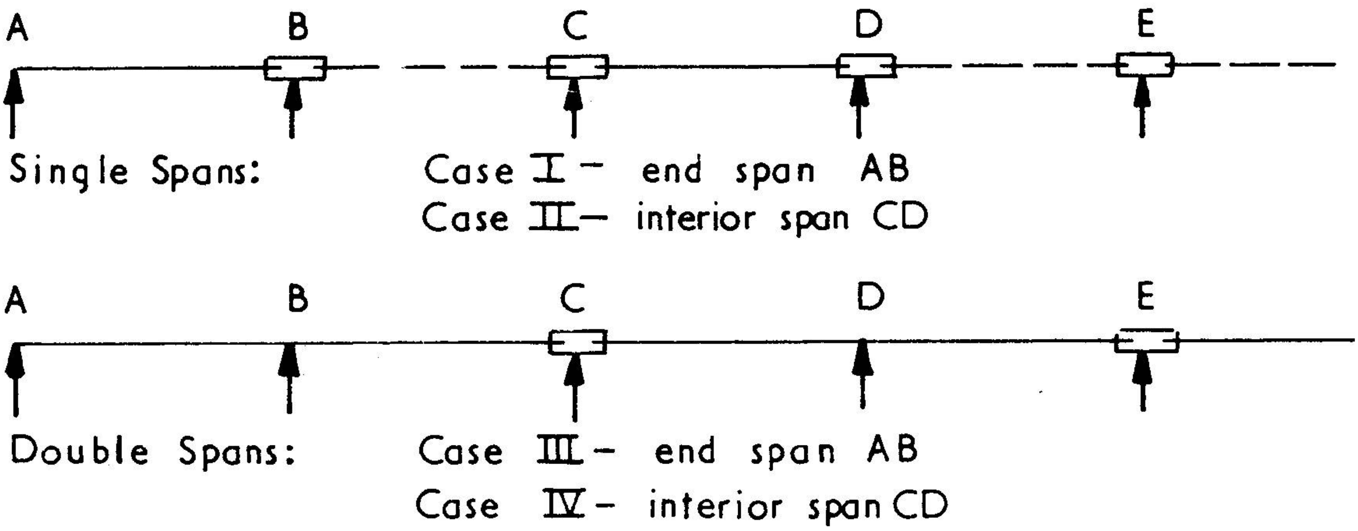

Fig 10 **Cases of Purlins Considered**

Case I End span of single span purlins.

Note, $M_A = 0$ and equation (2) does not apply, so that from equations (3) and (4) it may be shown that $M_B = 0.086WL$.

Case II Interior span of single span purlins.

Note $M_C = M_D = M$ say, so that using the form of equations (1) and (2) for span CD it may be shown that $M = 0.064WL$.

Case III End span of double span purlins.

Note, $M_A = 0$, equation (2) does not apply, and from continuity $\theta_{BA} = \theta_{BC}$. Hence from equation (3) and using the form of equations (1), (3) and (4) for span BC it may be shown that $M_B = 0.113WL$ and $M_C = 0.047WL$.

•Case IV Interior span of double span purlins.

Note, $M_C = M_E$, from symmetry $\theta_{DC} = \theta_{DE} = 0$, and equation (4) does not apply. Hence using the form of equations (1), (2) and (3) for span CD it may be shown that $M_C = 0.052WL$ and $M_D = 0.099WL$.

The bending moment diagrams for Cases I to IV are plotted in Fig 11.

8. Purlin Design

From Fig 11, it is seen that the maximum moment in a single span purlin is 0.086WL which leads to a required section modulus of $0.086\ WL/_{11.0} = WL/_{128}$. For a double span purlin, the midspan moments all result in stresses which are less than the nominal design stress so that midspan moments are not the criterion. Over the support D the moment in the unjointed purlin is 0.099WL and the permissible stress is 12.4 ton/in^2, so that the required section modulus for this position is $0.099WL/_{12.4} = WL/_{125}$. At the support B, the moment is 0.113WL but if the section is reinforced at this point with a standard sleeve joint, the criterion again becomes the design at support D.

The recommendation for design is therefore that the section modulus in inch units should be not less than $WL/_{125}$ and that a sleeve should always be used over the penultimate support, even in double span purlins.

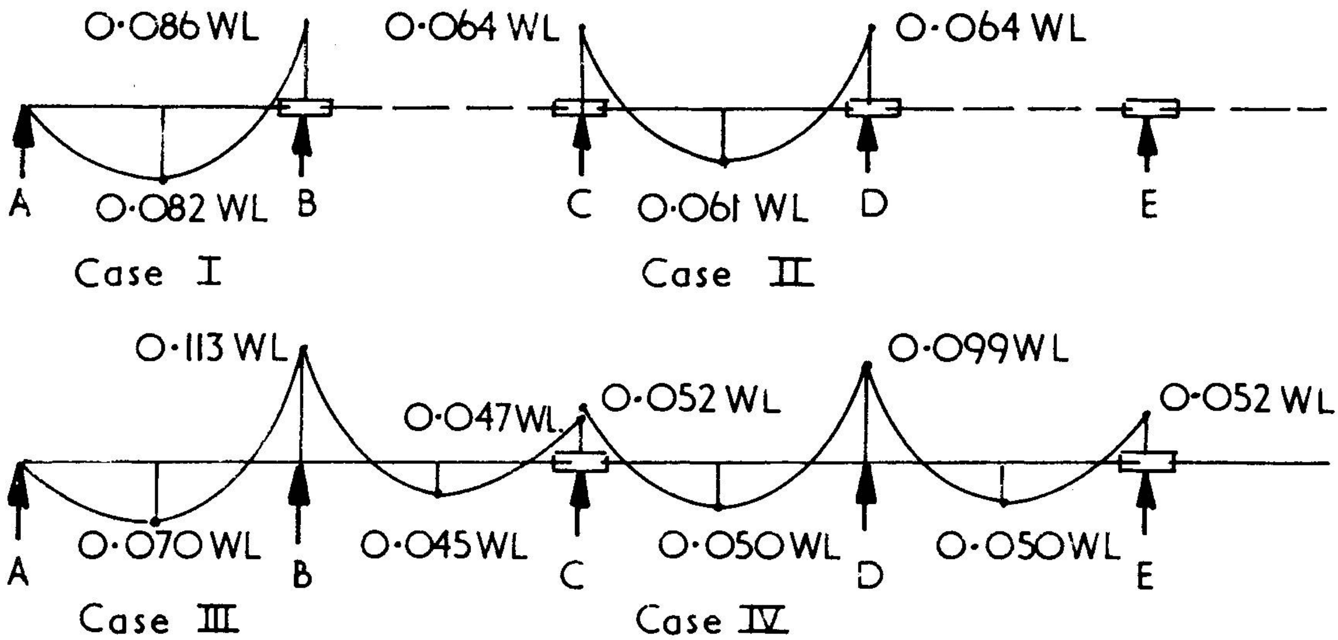

Fig 11 Bending Moment Diagrams for Purlins

9. Collapse Test on Existing Zed

Since the sleeve tests had been carried out on an existing type 7in x 2in x 14 gauge zed section, and the design method had been based on this section, it was considered advisable to carry out a full scale test on a pair of two 20ft span such purlins, jointed over the central support with one of the proposed sleeves. Each span therefore corresponded to the case of an end span in an actual building. Asbestos cement sheets were laid on the purlins and fastened with two hook bolts per sheet on one span and one hook bolt per sheet on the other span. The latter case represents the least lateral support that a purlin is ever likely to receive in practice.

With a section modulus of 2.0in^3, the proposed design load of a purlin on a 20ft span is $\frac{2.0 \times 125}{240} = 1.04$ tons, and at this load, under test, the midspan deflection was 1.13ins, ie span/212. The collapse load of the span with the least lateral support was 2.28 tons, and of the other, 2.43 tons. Thus the least load factor of the purlin in practice was 2.19, which was considered entirely adequate, and a justification of the design method.

10. New Range of Purlins

Using the design expression given in Section 8 of the paper, and applying it to various spans and loadings as indicated in Section 2, a new range of zed purlins was designed in metric units. The sizes in the range (depth in mm x flange width in mm) are 140 x 45, 170 x 55, 200 x 60, 240 x 75, and each size is rolled in two or three thicknesses. By this arrangement ten different sections are obtained with four roll settings. The range is designed to fit around the most common types of roof loading met in practice and so optimum economy is achieved.

11. Tests on New Range of Zeds

Since the expression for the section modulus (WL/125) and the proportions of the profile did not conform to the empirical rules set out in the British Standard for the design of zed purlins, it was obligatory to carry out full scale tests on all the purlins in the proposed range to ensure that the deflections at working load and the collapse loads were acceptable. To this end, loading tests of the type shown in Fig 12 were carried out on every purlin in the range, at the maximum recommended span. Tests were made using asbestos cement sheeting fixed with hookbolts (Fig 12) and steel sheeting fixed with self tapping screws (Fig 13).

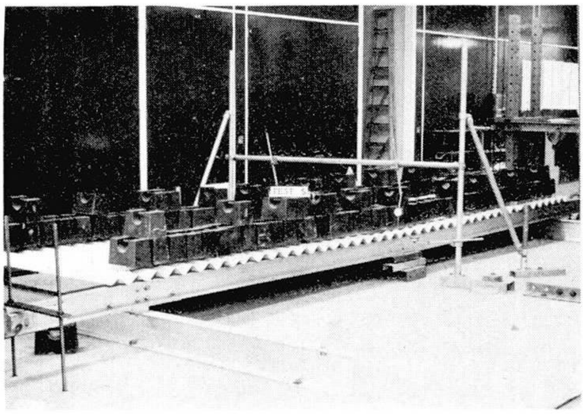

Fig 12

Test on Purlin with Asbestos Cement Sheets

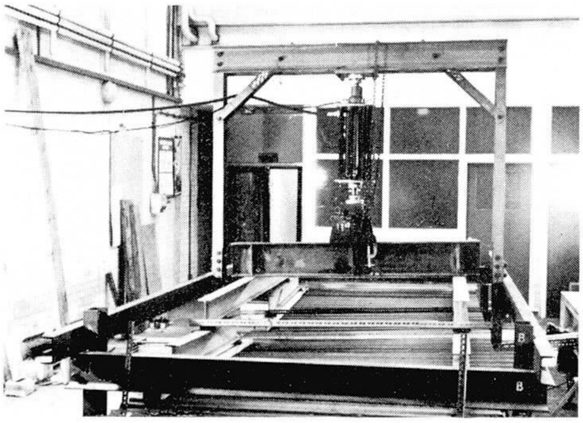

Fig 13

Test on Purlin with Steel Sheets

It must be appreciated that the results of these tests form the design criteria of the zed purlins. The design expressions obtained earlier are merely devices for proportioning the zed purlins, and consequently are only of secondary importance compared with the actual behaviour of the purlins under test.

It is not appropriate here to list the full results of the tests, but a summary is given of the deflections and load factors (collapse load/design load). At the design load the maximum deflections averaged span/$_{230}$ for the smaller purlins (spans up to 22ft 8in), and span/$_{210}$ for the larger purlins (spans up to 30ft 0in). The load factors obtained from the tests were about 2.10 for the smaller purlins and 1.80 for the larger purlins. It was found that the highest load factors were obtained when steel sheeting was used; no doubt this was due to the fact that more effective lateral restraint was afforded to the zed purlins by self tapping screws than by hook bolts.

12. Effect of Sag Bars

From the series of tests just described it was found that sag bars contribute little to the strength of zed purlins under downward load. In practice, their main use is to give rigidity while the sheeting is being fixed, but once this operation has been completed their structural effectiveness under downward load is quite nominal.

Under upward loading, such as wind suction, the situation is entirely different. In Britain, the new Code of Practice on wind loading means that the criterion of design for most roofs is now wind suction rather than downward load, as has been the case in the past. It was therefore considered important to carry out tests on zed purlins under reverse loading.

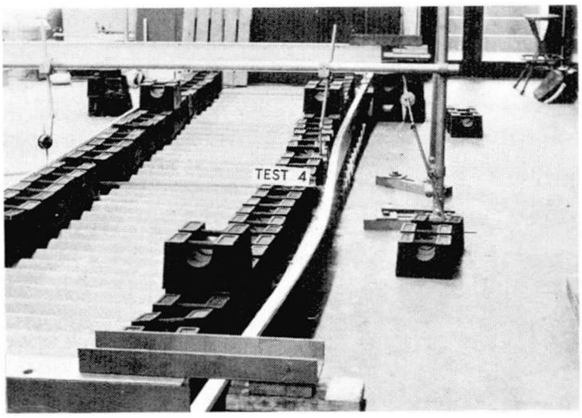

Fig 14 Reverse Loading Test on Purlin

Such a test is shown in Fig 14 using asbestos cement sheets fixed with hook bolts, which again represent the least lateral support likely to be met with in practice. The sag bar holes are positioned one above the other in the webs of the zed purlins and the sag bars are fixed to run from the bottom hole in one purlin to the top hole in the next. By this means maximum support is provided to the compression flange of the zed purlin. The effectiveness of the sag bar in providing lateral restraint is clearly seen in Fig 14, and the contribution of the purlin cleats and sleeves in preventing end rotation may also be observed.

From the tests using asbestos cement sheeting, it was found that the central deflection at the design load averaged span/$_{214}$ for the smaller purlins and span/$_{188}$ for the larger purlins. The load factors were about 1.80 and 1.55 respectively. These values are not significantly less than the values obtained under downward load, and if allowance is made for the fact that, in practice, the weight of the sheeting and purlins acts in an opposite sense to the wind suction, the results may be regarded as most satisfactory.

Reverse loading tests were also carried out on zed purlins using steel sheeting fixed with self tapping screws. The additional restraint, particularly the torsional restraint, afforded by these fasteners, reduced the central deflection to $^{span}/_{300}$ and increased the load factor to 2.22 for the smaller purlins tested.

From the tests it was found that one sag bar at midspan for spans up to 25ft 0in was adequate, but above this span two sag bars, spaced at $^3/_8$ of the span from each end, were necessary.

13. Comment on Tests

The test results confirmed the design assumptions and showed that, although zed purlins and asbestos cement sheets fastened with hook bolts gave entirely satisfactory results, zed purlins and steel sheets fastened with self tapping screws behaved even better.

Perhaps even more important than the actual test results was the fact that the full scale tests enabled the manufacturers to observe at first hand the behaviour of their product. As a result they have been able to answer with authority many questions which they could not have answered had the design been based on theory only. It is suggested that this intangible benefit of testing could be reaped for many other types of mass produced structures.

14. Bibliography

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SUMMARY

The paper describes the development of a new range of Zed-purlins. After a survey of market requirements and likely future trends, tests were made on various purlin sleeves in order to obtain an optimum design. Full scale tests were carried out on every purlin in the range to ensure that the behaviour was satisfactory. The beneficial effect of sag bars under reversed loading such as wind suction is described. Attention is drawn to the benefits which the manufacturer derives from testing.

RESUME

Le rapport décrit la mise au point d'une nouvelle série de pannes en Z. A la suite d'une étude de marché et de son évolution probable, des essais furent faits sur différents joints de pannes afin d'obtenir une constuction optimale. Toute une gamme d'essais furent exécutés sur chaque type de pannes pour s'assurer de leur comportement satisfaisant. On décrit ainsi l'effet bienfaisant d'une charge négative, comme l'effet de succion du vent, sur la déformation d'une panne et l'on insiste sur les avantages que peut tirer le fabricant de ces essais.

ZUSAMMENFASSUNG

Der Bericht beschreibt die Entwicklung einer neuen Serie von Z-förmigen Dachstuhlpfetten. Nach Untersuchung der Markterfordernisse und der wahrscheinlichen Zukunftsrichtungen wurden Versuche an verschiedenen Dachstuhlpfetten im Hinblick auf eine optimale Konstruktion durchgeführt. Umfassende Versuche wurden an jeder Pfette vorgenommen, um sich Gewissheit über ihr befriedigendes Verhalten zu verschaffen. Der günstige Effekt von durchhängenden Riegeln unter entgegengesetzter Belastung, wie Saugwirkung des Windes, wird beschrieben, und auf die Vorzüge hingewiesen, die sich für den Fabrikanten aus den Versuchen ergeben.