Design of cold-formed steel purlins

Design of Cold-Formed Steel Purlins

Calcul et conception des pannes en acier formé à froid

Bemessung von Kaltprofilpfetten

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SUMMARY
The alternative approaches to the design of light gauge steel purlins are reviewed and the reasons why the authors chose to design a new purlin system by testing are outlined. The test facility is described and it is shown how the test results were used as the basis for design expressions.

RÉSUMÉ
Les différentes variantes du calcul et du dimensionnement des pannes en acier formé à froid sont passées en revue. Les raisons pour lesquelles les auteurs ont choisi de concevoir un nouveau système de pannes au moyen d'essais sont soulignées. L'installation d'essais est décrite et il est montré comment les résultats d'essais ont été utilisés comme base des formules de dimensionnement.

ZUSAMMENFASSUNG
Es wird über verschiedene Ansätze zur Bemessung von Kaltprofilpfetten berichtet und begründet, warum die Verfasser für die Bemessung eines neuen Pfettensystems Versuche wählten. Die Versuchseinrichtung wird beschrieben und es wird gezeigt, wie die Versuchsergebnisse für die Bemessung verwendet werden.

1. INTRODUCTION

1.1 Purlin Cross-sections

In the U.K., cold-formed purlins and side rails usually have one of the cross-sections shown in Fig. 1. The conventional lipped Zed (a) has the disadvantage that the principal axis is inclined at about 17^o to the web giving rise to significant biaxial bending. The Zeta section (b) is a development which reduces this inclination to about 7^o so that on typical roof slopes the principal axis is near vertical. A lipped channel (c) has its shear centre outside the section so that load applied through the flange causes torsion as well as bending. Multibeam, (d) and (e), has a much more favourable position of the shear centre and the additional folds in the web improve its stability. Multibeam MK1 (d) is a well-established profile that has been used for many years. This paper describes some of the considerations which arose during the development of Multibeam MK2 which represents a considerable improvement in terms of performance as well as a more adaptable shape. This development will be described in terms of purlins although the procedures used are equally applicable to side rails and Multibeam MK2 is used for both purposes.

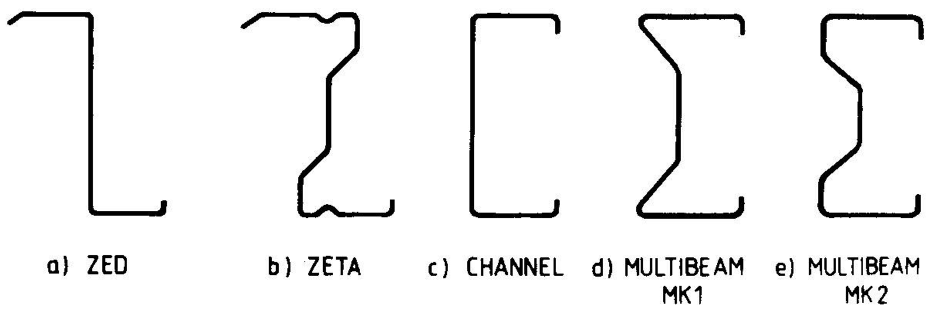

Fig. 1 Typical purlin sections

1.2 Purlin Systems

The above sections are used in the following purlin systems:

- Simple system: double span purlins with single spans in the end bays as necessary.
- Sleeved system: splicing members formed from short lengths of cold formed section at the internal supports provide semi-continuity.
- Overlap system: purlins are overlapped over the internal supports to provide full continuity together with reinforcement in the regions of maximum bending moment.

Despite the theoretical advantages of sleeved and overlap systems for longer spans, simple systems are widely used, particularly for the most common frame spacings of between 6 and 7 metres.

1.3 Design Procedures

Design procedures must take into account the following factors:

- The usual problems of unsymmetrical thin-walled sections, e.g. torsion, biaxial bending, local and lateral-torsional buckling, restrained warping.
- Restraint from the cladding, bearing in mind that the three major types of roof sheeting (namely, profiled steel or aluminium; asbestos cement and its substitutes; standing seam) all require

different treatment and that the behaviour can be further influenced by over-purlin insulation. It should also be noted that the downward load case, where the cladding restrains the compression flange in the span, is fundamentally different from the upward load (wind suction) case when the compression flange is largely unrestrained.

- The influence of anti-sag bars or other restraints within the span.
- The performance of simple systems using two-span purlins is considerably enhanced if advantage is taken of the redistribution of bending moments after first yield at the internal supports. The moment-rotation characteristics of "plastic hinges" forming over the centre supports is critically dependent on the section shape and the cleat detail.
- The moment-rotation characteristic of a sleeve must be determined experimentally.

There are four possible approaches to the design of a purlin system:

- Design by calculation using conventional code of practice procedures for unrestrained light gauge steel beams [1,2,3]. This implies elastic analysis and the neglect of any restraint from the cladding for the wind uplift case.
- Empirical design using safe approximate procedures as given for Zed purlins in many codes of practice e.g. [1,2,3]. This results in rather uneconomical designs.
- Design by calculation using specially derived procedures which take account of the stabilising influence of the cladding. There have been significant developments in recent years and some of these are reviewed in more detail in section 2.
- Design by testing which is the only way to take into account all of the factors listed above.

Design by testing was the authors' choice for the development of the Multibeam MK2 system shown in Fig. 1(d) because it provided the maximum possible economy for a given level of safety. Testing is, of course, relatively expensive but this was considered to be justified bearing in mind that a system was being developed for a projected production of about 2½ million metres per year for several years. Furthermore, by means of testing economic design can be extended to include systems for which theoretical methods are not currently available.

2. DESIGN BY CALCULATION

A number of simplified analytical approaches are available for the design of purlins restrained by roof sheeting although at the time of writing their relative merits and limits of applicability are not completely clear. These methods are all concerned solely with elastic behaviour and generally concentrate on the more problematical load case of wind uplift. Typically, the part of the cross-section in compression is considered as a column or beam-column restrained by an elastic spring where the spring represents rotational restraint from the sheeting together with an allowance for distortion of the cross-section as shown in Fig. 2. The value of the spring constant varies according to the particular purlin section, sheeting profile and fastener used and is probably best obtained from a simple test as shown in Fig. 3 although it may also be calculated.

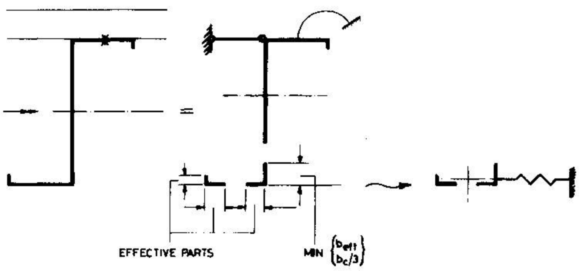

Fig. 2 Equivalent column on an elastic foundation.

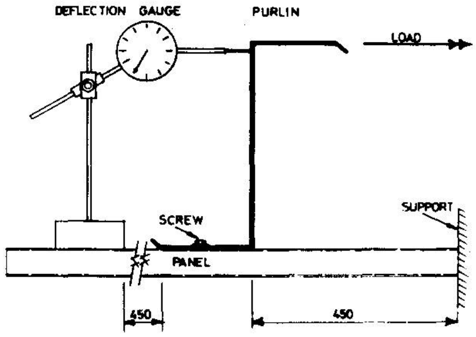

Fig. 3 Simple test for value of spring constant.

A calculation method for Z purlins with lips which is based on an equivalent column on an elastic foundation is included in the draft European Recommendations for the design of light gauge steel members [2]. This method was originally given by Sokol and is based on a calculation of the bifurcation load. It is therefore only strictly valid for sections with an axis of symmetry but appears to give good results for point-symmetrical Z sections. Pekoz and Soroushian [4] have given a procedure for both C and Z purlins which is based on a beam-column model. Thus, twisting of the section is included at all load levels and is not dependent on imperfections. They also include comparison with some test results. Schardt [5] has also described a calculation for Z purlins based on a beam-column assumption. This method is a development of the Pekoz approach which includes an allowance for the reduction in the effective depth of the section as a result of twisting. The latter two methods allow a non-linear load-deflection curve to be determined whereas the Sokol method gives only an estimate of the failure load.

Within the work of ECCS Committee TWG 7.1, the above three methods were compared with the results of 12 tests [4] on simply supported Z purlins subject to wind uplift and with depths in the range 200 to 245mm. The Sokol approach was chosen for inclusion in the European recommendations on the basis of simplicity and consistent safety. However, all three methods gave acceptable results and, bearing in mind the limited nature of the experimental comparisons, there is scope for further investigation. In particular, the extension to sections other than Z, the extension to multi-spans based on lengths between points of contraflecture and a wider range of section depths all appear worthy of more detailed consideration.

Application of the Pekoz method to the authors' test results for single span Multibeam MK2 purlins under wind uplift showed acceptable comparison between theory and test for section depths of 170 and 200mm but rather less good comparison for depths of 140 and 260mm.

A rather different approach has been adopted by Ings and Trahair [6]. Using a modification of the Barsoum and Gallagher finite element analysis [7], they carried out a study of C and Z section purlins restrained laterally but free to rotate at the level of the sheeted flange. The results of this study are presented in the form of non-dimensional design aids which are of more general application and a design procedure based on these aids is described. This procedure was applied to a series of 8 tests on C and Z section purlins with depths of 206 and 230mm. The comparison of theory and test is probably acceptable for practical purposes but does not appear to be as good as that given by the equivalent column methods considered earlier.

Methods are also available, such as the "generalised beam theory" [8], which are capable of taking account of most of the aspects of the elastic behaviour of purlins restrained by sheeting and giving good agreement with test results. Clearly, accurate design by calculation in the elastic range is becoming a practical possibility but if advantage is to be taken of the plastic redistribution of bending moments, it will continue to be necessary to resort to design on the basis of testing.

3. DESIGN PROCEDURE FOR MULTIBEAM MK2

As the simple system, based on two-span purlins, was crucial to the economy of the design, the design procedure was first established for this case. Design was based on a pseudo-plastic collapse mechanism as shown in Fig. 4 in which M_1 and M_2 are obtained from empirical design expressions deduced from tests on single span purlins as described later. The collapse load W_c may then be predicted using the following expressions.

$$W_c = \frac{2[M_2L + M_1(L-x)]}{x(L-x)} \quad \text{..................(1)}$$

$$\frac{x}{L} = \frac{(M_1 + M_2) - [(M_1 + M_2)^2 - M_1(M_1 + M_2)]^{\frac{1}{2}}}{M_1} \quad \text{.........(2)}$$

Having calculated the collapse load W_c, the plastic hinge rotation θ_p at the centre support at collapse is given by

$$\theta_p = \frac{L}{1.5EI}\left[\frac{W_cL}{8} - M_1\right] \quad \text{...................(3)}$$

where EI is the flexural rigidity of the purlins.

Investigation over a wide range of purlin sizes and spans as testing proceeded, showed that θ_p was generally in the range 2^o to 3^o and that 3^o represented a reasonable upper limit to the required rotation capacity.

Accordingly, a semi-empirical design expression based on equations (1) and (2) was adopted and this required the following steps:

(a) Determination of an empirical expression for M_1 at a plastic hinge rotation of 3^o using the simulated central support test described later.

(b) Determination of an empirical expression for M_2 based on simply supported purlin tests.

(c) Confirmation of this design procedure by comparison with tests on two-span purlins and the inclusion of a correction factor in order to increase the precision of the method.

The above procedure was first followed for purlins clad with profiled steel sheets and subject to downward load. Consideration of uplift loading and other cladding systems followed later.

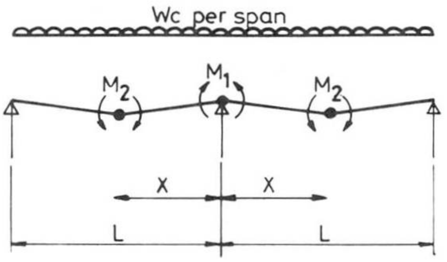

Fig. 4 Collapse mechanism for two-span purlin

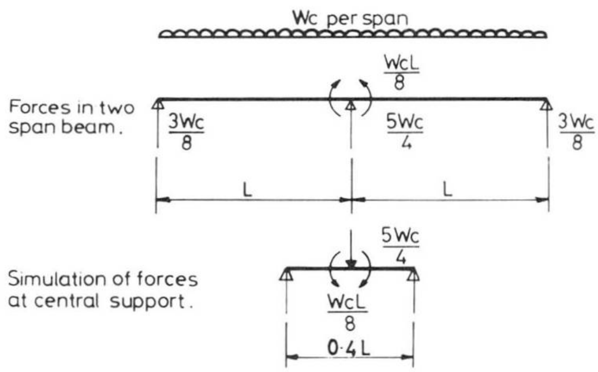

Fig. 5 Simulated central support test

4. DESIGN OF MULTIBEAM MK2 BY TESTING

4.1 Behaviour of Internal Supports

The behaviour at the central support has a great influence on the performance of a two-span purlin and trial profile shapes and their associated support cleats were investigated using the simulated central support test defined in Fig. 5.

The apparatus used is shown in Figs. 6 and 7.

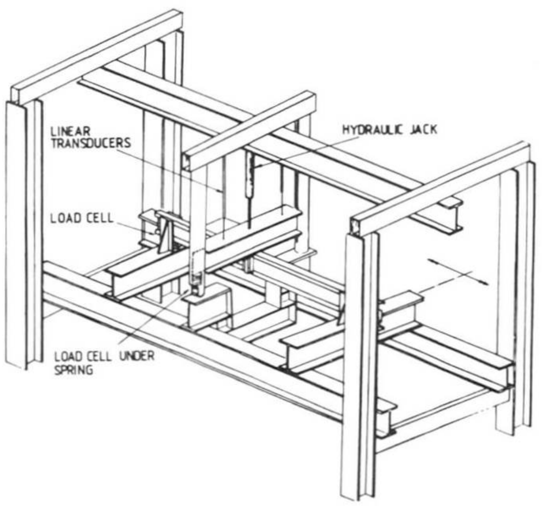

Fig. 6 Central Support test rig.

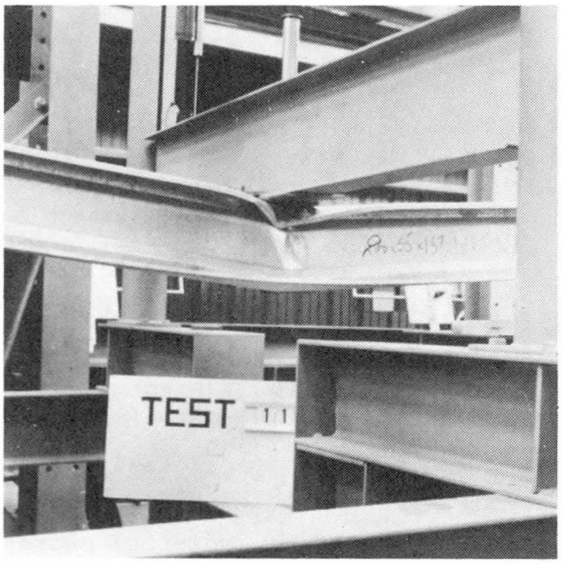

Fig. 7 Central Support testing

In carrying out this test, it was important to be able to determine the load-deflection relationship beyond the maximum load and well into the drooping post-failure region as shown for a typical test in Fig. 8. This can be achieved by loading with a screw jack or, as adopted by the authors, by the incorporation of a spring of suitable stiffness so that a hydraulic jack applies load to both the spring and the purlin and the resulting combination always has positive stiffness.

The cleat arrangement was found to be as important as the shape in ensuring a high maximum bending moment M_1 at the support together with a favourable performance in the post-failure region. A particular advantage of the shape of Multibeam MK2 is that it allows the use of a stiffened cleat with connection to the web at both top and bottom of the section as shown in Fig. 9. The enhanced performance of this detail far outweighs the additional fabrication cost of the cleat. It also has the advantage that it can allow the purlin or side rail to stand off the supporting member if this is required for the installation of insulation etc.

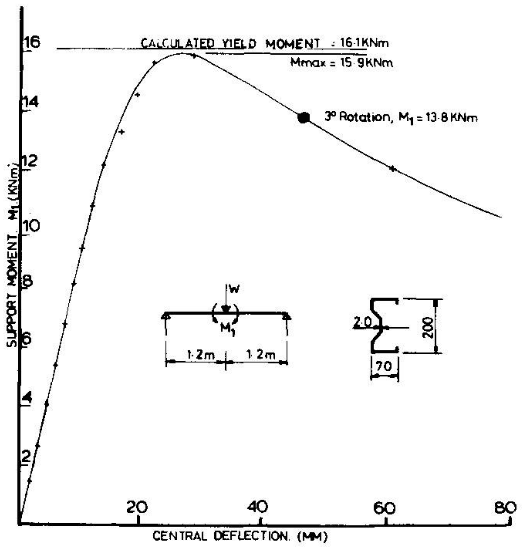

Fig. 8 Typical test result

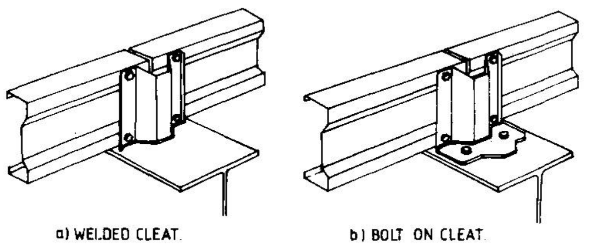

Fig. 9 Cleat details

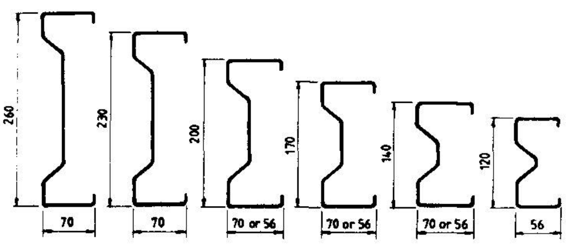

Fig. 10 Multibeam MK2 range

On the basis of the simulated central support tests, the broad details of the section range shown in Fig. 10 were established and a lower bound expression for the support moment M_1 at a plastic hinge rotation of 3° was derived. In general, the narrower flange widths are used for side rails where stability during erection is less of a problem.

4.2 Vacuum testing and application to downward loading

The remaining tests were carried out using vacuum loading on an assembly of two purlins and a 2 metre width of sheeting in the purpose-built apparatus shown in Figs. 11 and 12. For the first tests in this series, the weakest conventional steel roof sheet in the catalogue was chosen because the performance with metal roofing was considered to be the dominant design factor. Tests with standing seam roof sheets and asbestos-cement substitutes were carried out subsequently. Opportunity was taken to vary the number and type of anti-sag bars but the details used all represented practical arrangements that were under consideration for the final design. Anti-sag bars are required primarily to maintain the lateral stability of the working platform and generally carry only low stresses under downward load as the stability in the clad condition is provided mainly by the sheeting. However, their importance increases under wind uplift and with cladding systems that provide reduced restraint such as standing seam roofing.

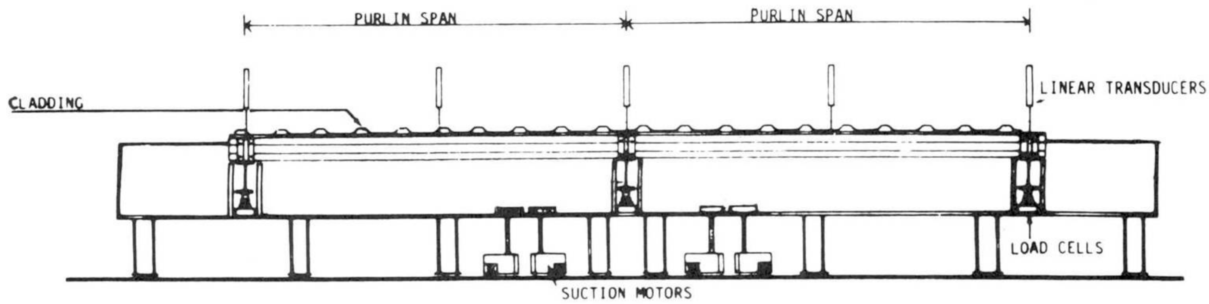

Fig. 11 Longitudinal section through vacuum testing apparatus

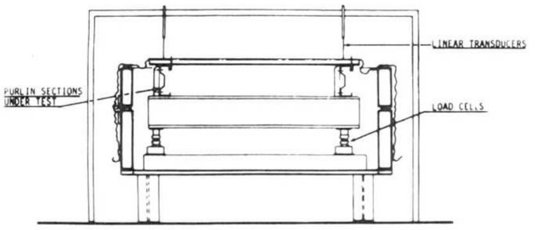

Fig. 12 Transverse section through testing apparatus

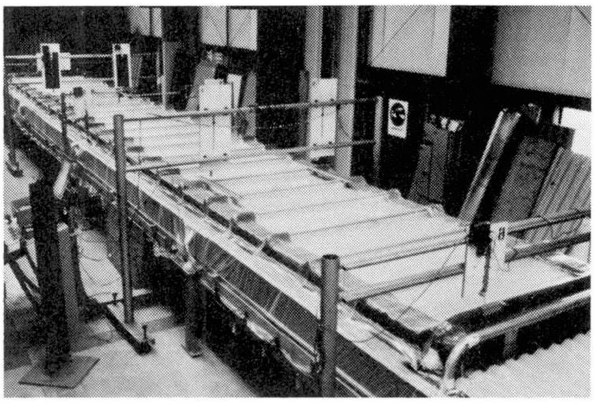

Fig. 13 Purlins under test.

Fig. 13 shows a typical assembly under test in this apparatus which was capable of accommodating single spans and up to two spans of 8 metres. In this way, a lower bound to the span moment M_2 was established on the basis of a series of tests on simply supported beams. The resulting design expression was then confirmed and empirically refined on the basis of 38 tests on pairs of two span purlins. Some refinement was necessary in order to improve the efficiency of the developed theory for purlins of 120 and 140mm depth. However, for purlins of 200mm depth and greater the unmodified theory gave slightly unsafe answers, presumably as a consequence of displacements at the points of contraflecture.

In all of these tests, the flanges of the two purlins faced in the same direction. This had the result of throwing slightly more load onto one of the purlins which usually failed first. The failure loads are therefore the lowest of the four tested spans in a test that is less favourable than the conditions encountered in practice.

The results of this procedure are summarised in Fig. 14. For a total of 30 tests covering the whole range of profile depth,thickness and span which were selected for the final range of sizes, the test results fall within -2% and +14% of the theory.

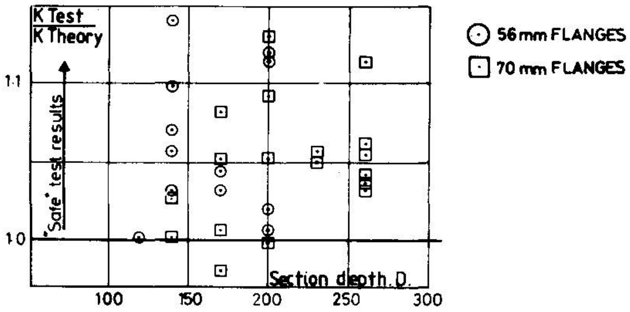

Fig. 14 Gravity load test results compared with theory

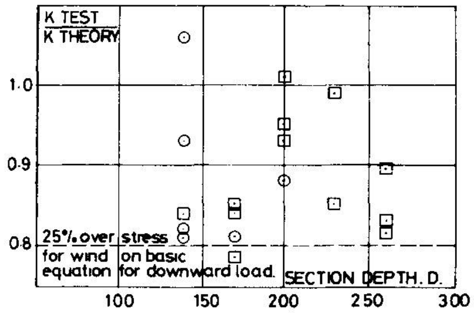

Fig. 15 Uplift test results compared with theory.

4.3 Uplift loading

Under wind uplift, the load capacity is reduced because the compression flange is unrestrained within the span. However, the current British Standard [9] allows a 25% increase of stress or a corresponding decrease to the load factor for wind loading and with steel sheeting fixed with self-tapping screws, it was found to be possible to balance the reduced load capacity against the reduced load factor as shown in Fig. 15. This means that for current U.K. usage, it is possible to use the same safe load tables for both upward and downward level. For other countries, however, different load tables are required.

With asbestos cement or other cladding fixed with hook bolts and for standing seam roofs, greater reductions of strength may occur. The precise reductions depend on the purlin depth, the span and the number and type of anti-sag devices. Values of these reductions based on tests are given in the manufacturer's literature.

4.4 Sleeved purlin system

The program described above was extended in various ways including the development of a sleeved purlin system. However, it is not possible to include a description of this additional work within the scope of this paper.

5. APPROVAL PROCEDURES IN OTHER EUROPEAN COUNTRIES

In the U.K. product approval is in the hands of the local authorities acting under the guidance of the Building Regulations and relevant British Standards. Design by testing is permitted and reputable companies use independent academics to verify their design procedures. The latest British Standard, which has yet to be extended to incorporate cold formed steel members, uses limit state methods with load factors of 1.6 for live loads and 1.4 for dead and wind loads. Deflection limits are at the discretion of the engineer but span/200 is commonly used.

During the course of the development of Multibeam MK2, Ward Brothers extended their interests outside the U.K. with sales outlets in the Netherlands and West Germany and a production facility in France. The building control system, in particular that for light gauge sections, differs in each country although all recognise the use of tests.

In West Germany and the Netherlands, buildings must be checked by a proof engineer who, in the absence of a codified design method, will ask for a product approval. In West Germany, this is granted by the Institut für Bautechnik on the basis of a report from a recognised independent authority.

In the case of Multibeam this report was prepared by Professor R. Schardt who assessed the test results against his general theory. Working loads are used in design with a factor of safety of 1.71 for both gravity and uplift loads. Deflection limits of span/200 apply. Similar procedures apply in the Netherlands but assessment and approval are provided by the National Building Research Centre, TNO. The factor of safety is 1.5 and the deflection limit is span/250.

In France, the need to insure buildings governs the procedure since, in order to obtain economic premiums, it is necessary to have the designs approved by a recognised Bureau de Controle. For items such as light gauge purlins proved by test, it is beneficial to obtain product approval from a Bureau which will then be accepted by the other COPREC members. SOCATEC were chosen to provide this for Multibeam. A limit state approach is used and the ultimate load is defined from test results as the lesser of 0.7 times collapse load or the load which causes a permanent deflection of 0.075 of the deflection at yield. The load factors are 1.5 for normal live loads, 1.3 for the normal dead loads and 1.0 for extreme loads. The deflection limit is span/200.

6. CONCLUSIONS

Although the design of cold-formed steel purlins and side rails solely on the basis of calculation is becoming an increasingly realistic possibility, good reasons remain for basing the design of any new system on testing. The comprehensive test programme and the semi-empirical design procedure used in the development of Multibeam MK2 for the U.K. market have been described and it has been shown that safe and highly efficient designs have been achieved. Approval of this product has been obtained or is being sought in other countries of Europe and some of the considerations encountered have been outlined.

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