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PROFILED SHEET STEEL CLADDINGS AS DIAPHRAGMS — A GENERAL REVIEW

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PREFACE

This general review forms the first part of a research programme undertaken by BRANZ to prepare design information for profiled sheet steel diaphragms associated with local steel and timber framed constructions. Such information is not readily available from current overseas standards, codes of practice and design guides.

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This paper is intended for other workers in the field of structural engineering research, and will also be of use to design engineers.

PROFILED SHEET STEEL CLADDINGS AS DIAPHRAGMS - A GENERAL REVIEW

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ABSTRACT

Light gauge profiled steel claddings can act effectively as structural diaphragms and in so doing can enhance a building's performance. Much work has been done overseas to establish standards, codes of practice and design guides in this field. Unfortunately, few of these are readily applicable in New Zealand because of differences in local products and practices.

This review forms the first part of a research programme aimed at establishing the appropriate guidelines and to provide basic data for using such diaphragm action in New Zealand. The aspects covered include the modes and conditions of diaphragm action, New Zealand and overseas practices as well as developments in design overseas. Future work needed to achieve the aim is discussed.

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INTRODUCTION

By the use of modern forming techniques, light gauge steel can be profiled to enhance overall strength and stiffness and to meet both functional and aesthetic requirements (various authors, see 1). Nowadays, the diversity of applications for profiled sheet steel in buildings is enormous. They range from roofing, decking, flooring and cladding as well as architectural finishes in domestic, commercial, agricultural and industrial buildings (various authors, see 2).

It has long been recognised (Johnson, 1950) that assembled systems of profiled sheeting, used as roof or wall cladding and properly fastened, besides being able to sustain loadings normal to their surface, can also display strong resistance to loads acting in their own plane. Such loads may be induced by wind, blast or seismic action, by frame-cladding interaction or by shell behaviour of certain types of roofs (Davies and Bryan, 1982). In all such cases, loads applied in the plane of the sheeting result in membrane stresses. The resulting stressed membrane is usually referred to as a diaphragm. In the complete assemblage, the sheets are stressed mainly in shear, while axial forces are resisted by framing members which carry them. This membrane, stressed skin or diaphragm action provides increased strength and stiffness to a building and can also be used to stabilise structural elements (various authors, see 3). In Europe, the method of structural design allowing for this action is normally termed 'stressed skin design' (Bryan, 1973c). However, to be consistent with the terminology commonly adopted in New Zealand, the terms diaphragm and diaphragm design will be used in this review. Also, the term panel is used to represent a sheeting and framing member assembly which forms part or the whole of the diaphragm.

In reality, diaphragm action always occurs in buildings whether or not it is taken into account in the design. If it is ignored, there exists the possibility that the sheeting or fastener may be overstressed even at working load. However, by properly acknowledging its existence, safer and more economical structures can be designed. Economic studies conducted in Europe involving various countries (European Convention for Constructional Steelwork (ECCS) and Constructional Steel Research and Development Organisation (CONSTRADO), 1976) indicated that savings of about 10 per cent of the total cost of the steelwork and sheeting could be achieved by considering diaphragm action in comparison with adopting conventional roof bracing in large rectangular clad structures.

Generally, the benefits of incorporating diaphragm action in the design can be summarised as follows:

- Efficient use of materials.
- Because claddings can serve the dual purposes as primary structure and covering surface, savings can be made in the cost of the structural framework. This can usually be done with little or no extra cost to the cladding or fixing.
- Reduced frame stresses and deflections compared with unclad frames, and elimination of structural members that would otherwise be required (various authors, see 4).
- The 'true' behaviour of the complete building rather than the idealised behaviour of the frame is examined.

- The elimination of bracing results in a clean looking clad structure which may better suit architectural requirements.

In the last thirty years, analysis of profiled sheet steel diaphragms has been the subject of considerable investigation (various authors, see 5) and established design methods are now used routinely overseas (various authors, see 6). However, not much of these methods or data is in a suitable form for immediate use by designers in New Zealand. This work forms the first part of a research programme undertaken by BRANZ to remedy this situation.

In this review, the modes and conditions of diaphragm action are first briefly outlined. Various overseas practices and developments in design are then generally reviewed. A summary of local practices is also included. It forms the basis for assessment of future work to prepare diaphragm design information for local constructions. Finally, a bibliography is presented to assist designers and research workers to obtain background information.

This review concentrates on profiled sheet steel applications in conventional low-rise steel or timber framed building structures. Multi-storey buildings and special frameless structures involving roof shapes in the form of folded plates, cylindrical shells and hyperbolic paraboloids (ECCS, 1977) which may rely almost entirely on in-plane resistance of profiled sheetings, are not included.

STRUCTURAL MODES OF DIAPHRAGM ACTION

A panel of light gauge profiled steel sheeting only contributes to the strength and stiffness of a building when such inherent characteristics are mobilised by deformations in its own plane.

When a flat-roofed building with non-rigid frames is subjected to lateral loads (Figure 1), each roof panel acts as a diaphragm transmitting the load back to the gable ends which are properly stiffened. This is analogous to the roof functioning as a deep plate girder where the roof sheeting acts as the web and transmits the displacement forces to the rigid end gables by means of shear field in the sheeting; and the eave purlins and the end gables resist axial forces induced by bending and end-reactions respectively. Buildings with flat roofs receive no contribution from this in-plane action in resisting vertical loads.

For a pitched-roof building with flexible or unbraced intermediate frames (Figure 2), besides resisting lateral loads as described, the in-plane action also contributes positively to resist vertical loads. For these structures, the component of the vertical load along the roof slope also mobilises the in-plane resistance of the roof diaphragm which in turn prevents the frames from spreading outwards. The flatter the pitch of the roof the less effective is this resistance, but the more effective it is under lateral load.

When the cladding is used as walls in a conventional building (Figure 3), they can also act effectively as vertical cantilever diaphragms to control sway. The behaviour is similar to that of horizontal roof diaphragms.

The strength of the cladding connections is generally critical with regard to the ultimate shear capacity of the diaphragm assembly (various authors, see 6).

NECESSARY CONDITIONS FOR DIAPHRAGM ACTION AND DESIGN

In order that diaphragm action be used safely and the design be reliable, nine conditions must be satisfied (various authors, see 7):

(1) The cladding materials which form the diaphragm should have a high degree of reliability as regards both strength and stiffness and preferably also exhibit ductility so that redistribution of forces can occur. They should be designed for their primary purpose as cladding unless a separate cladding is provided for the purpose.

(2) The claddings and fixings shall be suitably protected so as to ensure durability, i.e., maintain a satisfactory appearance and performance throughout the design life; and have adequate fire resistance (BS 5427, 1976). Generally, because the membrane stresses are relatively small compared with normal bending stresses, the claddings will fail in primary bending first even if corrosion were to take place. Nevertheless, proper attention must be paid to the possibility of accelerated corrosion at the connections due to dissimilar metals in contact, and relevant advice to guard against this is well documented (Corrugated Steel Manufacturers' Association et al, 1981; Thomson, 1987).

(3) The claddings must be positively connected to their supporting members, and laps of adjacent sheets must also be firmly fastened so that diaphragm forces can be transmitted through successive sheets. It is essential that the fasteners will not work loose during service and undesirable for them to fail prematurely in a brittle manner. They should be able to sustain the forces arising from diaphragm action as well as from wind uplift, if appropriate.

(4) Suitable structural members and associated connections should be provided to transmit forces arising from diaphragm action to the main structural framework and thence to the foundation.

For roof diaphragms, the edge members in the direction of the span of the diaphragm and their intermediate joints should have sufficient capacity to carry the longitudinal forces arising from diaphragm action, as in the flanges of plate girders; and the connections to the rafter must be adequate. The end gables must be properly braced so that the diaphragm force in the roof claddings can be taken down to the foundations. Otherwise, the claddings will have a negligible effect, they may merely participate in distributing concentrated lateral load on the building between frames, but will not help in the case of a uniformly distributed lateral load.

(5) Significant panel openings are undesirable and certain restrictions regarding area and position are necessary.

(6) The design must be based on established analytical procedures or by standard tests.

(7) It is desirable that diaphragms be designed so that the failure mode is ductile.

(8) Diaphragm action should be used primarily to resist wind or snow loads which are applied through the cladding; so that if the cladding is removed, so also is most of the load. It is also suitable for resisting other transient dynamic loads, e.g., surge

forces from overhead cranes or earthquake wave loads. Diaphragm action should not be used to resist large permanent loads because accidental damages or inadvertent removal of the claddings for maintenance, extension or modification purposes could prove disastrous.

(9) For those structures in which diaphragm action provides complete or partial stability of the structure, proper precautions should be taken when it is necessary to remove a vital portion of the cladding or associated structural members which transmit the diaphragm forces to the foundation.

NOTES ON SOME ASPECTS OF PROFILED SHEET STEEL DIAPHRAGMS

General Proportions and Fixing

The effectiveness of a diaphragm relies on the appropriate ratio of span to depth. In general, for flat-roofed buildings, the length between stiffened frames should be less than four times the depth; whereas for pitched-roof buildings, the corresponding length should be less than two and a half times the depth (Davies and Bryan, 1982). For longer buildings, intermediate stiffening frames should be used. Normally, unless the diaphragm is very lightly loaded, deflections are likely to be excessive or the benefit of diaphragm action small if the ratio of span to depth of the diaphragm exceeds about four.

Fastening on all four sides of a diaphragm assembly, i.e., incorporating shear connectors, will produce a more efficient diaphragm than that where sheets are fastened at seams and on to perpendicular members only.

Flexibility and Strength

The flexibility of a complete diaphragm assembly is dependent on the flexibilities of the individual components, including the claddings themselves, the connections and the supporting framework; and the strength is controlled by that of the most highly stressed part (various authors, see 8).

Seam and Shear Connector Fasteners

For most diaphragms, the overall strength is likely to be dictated by the capacity of seam connections or sheet to shear connector connections (if adopted) (various authors, see 6). These connections should be designed such as to obtain failure by tearing of the sheeting at the fastener rather than by shear failure of the fastener itself. The first mode allows failure to occur gradually in a ductile mode and permits force redistribution to take place; whereas the latter occurs suddenly without warning.

Purlin Fasteners

For profiled sheet diaphragms it has been found that if the cladding is fastened at every corrugation along the purlin, the diaphragm is usually much stiffer than if fasteners are used only at alternate or less frequent corrugations. However, provided fasteners are used in every corrugation at eave and/or ridge purlins, the diaphragm is very nearly as stiff as if fasteners are used in every corrugation at every purlin. This is convenient because one generally needs to fasten every corrugation at eave and/or ridge purlins in order to cater for the requirements of high local wind suction. Consequently, these fasteners are used to good purpose both by wind suction and diaphragm action and should be designed accordingly. Fastening through the trough of the cladding also resulted in a much stronger and stiffer diaphragm than adopting crest fixings (Davies and Bryan, 1982).

For diaphragms associated with thin sheetings of shallow depth, buckling of the claddings (Davies and Bryan, 1982; Turnbull et al, 1975, 1982, 1985; Gebremedhin and Irish, 1986) may be the critical mode of failure whereby a number of buckling waves develop across the panel. This type of failure is related to the purlin spacings as well as the spacings and withdrawal capacity of the purlin fasteners; especially those located at or adjacent to the crest of the buckling wave. Thus the purlin fasteners may be influential in confining the buckling of claddings to between purlins or prohibit its development.

Purlin or Perpendicular Member Spacing

In general, for the same pattern of fastening along the purlin, increasing the number of purlins (or perpendicular members) will increase the number of purlin fasteners thus resulting in a stronger diaphragm. However, this benefit may no longer apply when the seam connections are strong and the overall diaphragm strength is controlled by other failure modes, e.g., sheeting failures (White, 1986).

Erection

Proper attention must be paid to the erection of all diaphragm-assisted structures as they only act as a load-resisting unit when the whole surface and associated framework are completed. Thus temporary bracing may be essential during construction (CONSTRADO, 1973a).

OVERSEAS PRACTICES

Australia

The traditional practice in Australian domestic constructions has been to crest-fix the roof sheeting, especially corrugated sheeting, to minimise leakage problems (Nash and Boughton, 1981). However, trough fastenings have also been adopted to ensure more efficient diaphragm action (Beck, 1973; Sved, Rehn and Lawrence, 1972). Based on manufacturers' and suppliers' information, the profile height of common trapezoidal sheeting ranges from 16 mm to 38 mm. Typical steel thicknesses are 0.45 mm and 0.8 mm while the nominal yield stress can be 300 MPa or 550 MPa (Maricic, 1979; John Lysaght (Australia) Limited, 1980a). The usual recommendation for fastening to steel or timber frames is to use hexagonal head roofing screws with neoprene washers. Side laps are generally fastened by lapstitch screws.

Western Europe

In Britain, both sinusoidal and trapezoidal profiles are used (CONSTRADO, 1980; Roofing, Cladding and Insulation, 1985, 1986); although most British architects tend to specify trapezoidal profiles for use horizontally and vertically due to their sharper appearance (Brookes, 1984). The steel thickness and profile height generally range from 0.4 mm to 1.2 mm and 19 mm to 90 mm respectively. Self-drilling self-tapping screws, wood screws, self-tapping screws and rivets, as appropriate, are the usual means of fastening to framing members and for seams. Trough fixing is a common practice. Also, a number of standard public building systems, e.g. CLASP, SEAC, SCOLA have used the roof deck as a diaphragm in the construction of schools, college, library and other public buildings (Bell, 1984; Bryan, 1973b; Davies and Bryan, 1982). Other applications include commercial and industrial buildings as well as nursery schools (Davies, Nemir and Taylor, 1986).

In Sweden, surface elements are normally made up of channel sections of relatively high profiles, i.e., 50 mm to 112 mm (Baehre, 1975a). Joints primarily applied are riveted and non-conventional screwed connections. Common sheetings are of high yield steel with nominal yield stress of about 340 MPa.

North America

For steel-framed buildings, common North American diaphragm practice involves welding profiled sheeting to perimeter members in every corrugation and on all four sides to produce a very strong diaphragm (Lawson, 1976c). Seam welding is generally performed on an upstand overlap to reduce the risk of poor fusion, and this is reflected in a high strength factor to allow for the variability of site welding. One feature of American practice not found in Europe is that the sheets are often puddle-welded to the steel framework and to each other. This is because the much higher wind, snow and earthquake loads experienced in North America make welding appear more viable than in, say, Britain.

In the United States of America, the panels used for such installation include those having open corrugated cross-section as well as cellular section made by spot welding hat sections to flat sheets. Steel thickness and panel depth range from 0.5 mm to 2.5 mm and 40 mm to 150 mm respectively. Various systems of fastening are employed depending upon strength requirements and economy and include self-tapping screw fasteners, welds and clinched seams (CONSTRADO, 1977a, 1977b).

In Canada, the combination of welding and button punching of seams are used to lower site cost, the design is generally carried out by extrapolating test data (Canadian Sheet Steel Building Institute (CSSBI), 1972).

For timber-framed constructions, light gauge steel roof and wall systems have been used in North American agricultural and commercial buildings for many years (various authors, see 9). The cladding is fastened to the structural framework with nails or screws while for side laps, self-drilling self-tapping screws, stitch screws as well as glue (White, 1978, 1986) have been used. Both trough and crest fixings have been used. In Canadian farm buildings, the steel thickness and profile height generally range from 0.3 mm to 0.46 mm and 16 mm to 25 mm respectively (Agriculture Canada, 1985).

DESIGN

Design of Diaphragm Panels Associated With Steel Framing Members

For profiled sheet steel diaphragm panels associated with steel framing members, various design approaches have been developed mainly to address the problems of flexibility and strength (various authors, see 8). Most of the research work in North America and Western Europe has been concentrated on trapezoidal profiles employing trough fixings because of their efficiency and wider applications. Sinusoidal profiles are less popular subjects for study. The design approaches developed include testing, simplified equations, finite element methods and design tables.

Testing

The in-plane characteristics of a diaphragm can be determined on the basis of test loading the diaphragm panels. These tests with regard to system and loadings, are as near as possible equivalent to the actual mode of action. The test procedures are well documented (American Iron and Steel Institute (A.I.S.I.), 1967). Both cantilever panel tests as well as full scale tests can be performed. For unusual shapes or arrangement of diaphragms, testing is still the most reliable method if boundary conditions are correctly simulated. Nevertheless, not all the desirable information can be gained from tests apart from deformations, failure loads and modes. Testing is generally time-consuming and uneconomical as a design tool.

On the other hand, tests of connections between sheeting and framing members and sheeting to sheeting are essential in order to obtain the basic flexibility and strength data for analysis or design by calculations. The appropriate test methods are well documented (ECCS, 1978, 1984) and extensive tests have been carried out to collect design data for common practices overseas (Davies and Bryan, 1982; Grimshaw, 1979).

Simplified Equations

For general design purposes, calculations may proceed on the basis of an assumed distribution of internal forces which satisfy the requirements of equilibrium. The approximate internal force distribution can be established by tests or other refined methods, e.g., finite element methods.

Various equations based on this approach have been developed, mainly for trapezoidal sheeting with trough fixings employing mechanical or welded connections (various authors, see 10). The permissible strength is normally determined by comparing different failure modes while overall flexibility is obtained by summing the flexibilities of the constituent elements.

In general, this approach is useful, efficient and very attractive as a design tool. However, it still has its limitations in that the equations are normally applicable to diaphragms of a particular form.

Finite Element Methods

When unusual features or need for greater accuracy justifies the more refined analysis, finite element methods employing the use of computers can be used (various authors, see 11). The complete diaphragm is modelled as an assemblage of three types of elements; the individual sheet sections, the connectors and the supporting framing members. Stiffnesses of the sheeting and the frame can be established either analytically or by experiments, while those for the connections can only be obtained by tests, and analyses proceed using conventional matrix methods.

Both linear and non-linear finite element analyses have been developed and established computer programmes are available for commercial use. Non-linear analysis essentially takes into account the nonlinearity of the connections (Atrek and Nilson, 1976, 1980). However, it is generally agreed (Atrek and Nilson, 1981; Davies, 1980b) that for practical purposes, the complexity of the full non-linear finite element analysis is unnecessary.

In this respect, it has been demonstrated (Davies, 1972, 1973, 1977; Davies and Lawson, 1978a) that analogue frame analyses can replace complicated finite element analyses and produce satisfactory results for design.

Design Tables

It is also possible to quickly produce solutions to flat roof designs without the need for detailed analyses. This can be achieved through design tables based on simplified equations (Bryan and Davies, 1981) which give in a simple form the strength and stiffness of profiled sheet steel roof diaphragms. The tabulated results are generally valid for a particular assumed condition using data related to profile dimensions, fixing specification and sheeting layout patterns. It can be appreciated that compiling design data in a general tabular form involves the use of a number of conservative assumptions and as the number of variables is reduced, the design tables become simpler but also less economical in many cases, but even so they may still be adequate.

Design of Diaphragm Panels Associated With Timber Framing Members

The investigations of diaphragms of light gauge profiled steel sheeting associated with timber framing members (various authors, see 12) are less extensive than those associated with steel structures. Most of the work is related to agricultural and domestic buildings and the design is normally carried out by direct panel tests or by extrapolation of test data. Relatively little effort (various authors, see 13) has been devoted to the establishment of simplified equations. Diaphragms studied are usually fastened with screws. The established prediction procedures for steel-framed panels employing simplified equations or finite element methods cannot be immediately applied to timber-framed light gauge metal diaphragms because their validity is not confirmed by experiments. There is also a lack of basic information on connection characteristics.

Design of Sheeted Buildings

For steel structures, on the basis of the deformation modulii of roof and wall diaphragms (deformation per unit load acting in the plane of the diaphragm), a building made up, for instance, of wall and roof diaphragms or roof diaphragms and frame can be designed for the working range in accordance with elastic theory using established structural principles (Davies and Bryan, 1982; ECCS, 1977). If the wall and roof diaphragms or roof diaphragms and frame have sufficient deformation capacity while retaining their load capacity, then the building can be designed for the ultimate range according to the plastic theory (Davies, 1973; Davies and Bryan, 1982; ECCS, 1977). Studies on sheet steel buildings have included the effects of various factors such as insulation (Lapin, 1974), noncontinuous sheets (Davies and Bryan, 1982), roof light openings (Davies and Lawson, 1978a) and concentrated loads (Davies, 1978a). The correlation between theory and measured results for tests on sheeted buildings are generally satisfactory (various authors, see 14).

With timber-framed buildings, relatively little work has been carried out to establish analytical methods incorporating full interaction between profiled sheet steel diaphragms and the building framework or to verify this type of diaphragm action in complete buildings using full-scale tests (various authors, see 15) though it could be argued that classical structural principles are equally applicable.

STANDARDS, CODES OF PRACTICE AND DESIGN GUIDES

For profiled sheet steel diaphragm design associated with steel structures, relevant national standards, codes of practice or design guides either exist or are in draft form in Australia (Standards Association of Australia (SAA), 1974), Britain, Canada, Czechoslovakia, Germany, Holland (TNO, 1979), Poland, Sweden (Swedish Institute of Steel Construction, 1982) and the United States of America.

The pioneer research in the United States of America was carried out in Cornell University (Nilson, 1956). The American Iron and Steel Institute published a code on steel diaphragm design in 1967 and this was accepted as the reference practice over the years. The latest version of this code (A.I.S.I., 1987) has just been released. For many years, no fundamental theoretical analyses were given for the strength characteristics of a roof diaphragm. The code instead prescribed that each type of diaphragm which is different from one of the standard sections previously investigated be subjected to tests. Standardised methods of conducting panel tests to determine the strength and flexibility characteristics are given. The latest code now contains guidelines on design by calculations.

In the United States of America, other established design guides employing empirical and semi-empirical methods of design include one published by the Steel Deck Institute (Luttrell, 1981) and another published by the Departments of the Army, the Navy and the Air Force (1982). The former is presented in a limit state format and the method can be used with any fastener or combination of fasteners as long as the connection characteristics are known. The latter is in a working stress format, the equations presented have been derived empirically to fit test data and apply to horizontal diaphragms of buildings having sheets with welded connections to the support members, and button punching or welding for seam connections.

In Canada, there are no standards for the design of light gauge metal diaphragms in steel constructions. There is, however, a design guide (CSSBI, 1972) based on an empirical approach developed from tests conducted for the U.S. Army. Nevertheless, the original work was conducted quite some time ago and it was because of its age and empirical nature that alternative approaches, mainly in simplified equations, were further explored by Canadian research workers (various authors, see 16).

In Britain, a draft standard (British Standards Institution, 1978) containing relevant clauses for 'stressed skin design', was released for public comment in 1978. It is understood (Lazenby, 1985; Private communication, 1987) that work will soon commence on preparing BS 5950, Part 9: Structural use of steelwork in building, code of practice for stressed skin design, under the chairmanship of Prof. E.R. Bryan.

Even though a complete British Standard on 'stressed skin design' is not yet available, extensive work in this field has been carried out over the years by Prof. E.R. Bryan, Prof. J.M. Davies and associated workers, first at the University of Manchester and later at the University of Salford (various authors, see 17). This has led to the publication of a design manual in 1973 (Bryan, 1973c) and then a more comprehensive and general manual on 'stressed skin design' in 1982 (Davies and Bryan, 1982). These documents present design methods for sheeted buildings, i.e., conventional single storey buildings with flat or pitched roofs and with a variable number of pinned or rigid frames. They permit theoretical design of roof diaphragms made up of commonly adopted sheetings, purlins, main members and connections. Some fundamental data, primarily the strength and flexibility characteristics of common connections, which are based on tests, are given. The manuals contain tables which very largely facilitate design.

Parallel to this work, with an aim to simplify the process of designing small flat roofs, design tables (Bryan and Davies, 1981) have also been prepared which enables routine design to be carried out efficiently.

On the whole, the most significant development to date in Europe is the publication of the European Recommendations for the Stressed Skin Design of Steel Structures (ECCS, 1977). It contains the full design method including diaphragm design using simplified equations or cantilever diaphragm tests, and the application of diaphragm action to complete structures together with examples.

The new Polish recommendations for 'stressed skin design' is generally based on ECCS recommendations, as well as the results of extensive theoretical and experimental investigations carried out in Poland (Brodka, Garncarek and Grudka, 1986).

It has been well accepted (various authors, see 6) that the basic characteristics of connections in diaphragms are essential for design by calculations. Although theoretical solutions have been attempted for mechanical connections (Baehre and Berggren, 1973; Toma, 1978b; Strnad, 1979), they generally have the limitations of lack of generality and being grossly conservative for strength computations while few attempts have been made in presenting expressions for flexibility (Davies and Bryan, 1982). Thus it is commonly accepted that these data should be obtained from tests and the European recommendations (ECCS, 1978, 1984) have been prepared for this purpose. For welded connections, design expressions (Pekoz and McGuire, 1979) which incorporate various parameters, are feasible for design.

For profiled sheet steel diaphragm design in timber structures, design by testing is largely based on the American recommendations (A.I.S.I., 1967). Relatively little work (various authors, see 13) has been done on establishing standards, codes of practice or design guides based on simplified equations and tables. There are also no standards for the testing of connections associated with light gauge metal diaphragms and timber supporting members.

NEW ZEALAND SITUATION

Up to the present time, diaphragm design of profiled sheet steel in New Zealand has been inhibited by the lack of appropriate provisions in New Zealand Standards or other design recommendations appropriate for New Zealand use.

A preliminary survey by BRANZ (Brookes, 1984) identified some essential differences between profiled metal systems in New Zealand and those produced in Britain. Those which are likely to affect diaphragm design are: (1) the yield strength and gauge of steel sheet, (2) profiles, and (3) methods of fixing.

(1) Yield Strength and Gauge of Steel Sheet

The bulk of steel used for claddings in the United Kingdom has a minimum lower yield stress of 220 MPa. And the high tensile steel for similar applications used by U.K. roll formers has minimum lower yield stresses of

350 MPa and 550 MPa (BS 2989, 1975; CONSTRADO, 1980). In New Zealand, the commonly used sheeting has a minimum yield strength of 550 MPa, although those having corresponding values at 250-330 MPa (which is similar to profiled steel products in Sweden) are also available.

Sheet steel thicknesses are usually 0.4 mm and 0.55 mm in New Zealand whereas those in Britain are 0.5 mm, 0.75 mm, 1 mm and 1.2 mm

Use of higher strength materials in claddings allows the reduction of material thickness which entails a greater slenderness ratio in the unstiffened cross-section. This may affect the local and overall buckling as well as deformation characteristics of the cladding and the behaviour of the connections (Davies and Bryan, 1982) when such claddings are used as structural diaphragms.

(2) Profiles

Both sinusoidal and trapezoidal profiles are common in Britain and New Zealand. However, in New Zealand, the 'rib and pan' profiles are also popular in domestic buildings. The form for common local sinusoidal profile is generally in accordance with NZS 3403 (1978) which has a nominal profile height of 19 mm while the profile height for common trapezoidal profiles ranges from 25 mm to 58 mm.

(3) Methods of Fixing

'Rib and pan' profiles normally use a secret clip fixing device. The suitability of this fastening method in diaphragm design has not been seriously investigated though it is a commom belief (ECCS, 1977) that fixings relying on friction are unsuitable for transmitting diaphragm forces.

It is the normal practice in Britain to fix sinusoidal sheeting through the crest of the corrugation, but the usual method for trapezoidal sheeting is to fix through the troughs to avoid spreading of the sheeting. In general, trough fixing is preferred for efficient diaphragm action.

In New Zealand, crest fastening has been used traditionally irrespective of the sheet profile and types of construction. It is the common belief that this practice reduces the possibility of leakage in comparison with trough fixings. Nevertheless, trough fixings have been used in wall constructions. When trough fixings are used, the designer's attention is drawn to the necessity of ensuring adequate and permanent sealing to prevent the ingress of water flowing in the trough.

Both steel and timber framing are used locally. Timber constructions are common in domestic buildings and low-rise commercial buildings while steel is more dominant in heavy industrial applications. For timber structures, the purlins are mainly of Radiata pine (Whiteside, 1984) whereas for steel structures, the purlins are normally of cold-formed sections of galvanized high yield strength (450 MPa) or black (280-340 MPa) steel with thicknesses of 1.6 mm, 1.9 mm or 2.5 mm depending on the strength or stiffness required.

Various systems of fastening the claddings to structural members are employed locally, depending upon strength requirements and economy. They include self-drilling self-tapping screws for steel structures and self-drilling wood screws, plain shank or helically threaded nails for timber structures. Neoprene sealing washers are commonly used. Various cladding manufacturers also recommend self-tapping screws or rivets as seam fasteners if required.

Even with these differences between overseas and local products and practices, the stiffening effects of roof and wall claddings will be similar and cannot be ignored. Clearly, if the cladding to structure fixings are adequate, a substantial contribution would be made by the sheeting. This is particularly advantageous because of the high usage of profiled sheet steel in domestic house constructions; and such constructions form a major part of the New Zealand building industry.

FUTURE WORK

In order to make it possible to perform diaphragm design using analytical methods for New Zealand claddings, the basic data for commonly adopted connections needs to be collected. For trough fixings associated with steel structures and for seam connections, recognised test procedures are well established (ECCS, 1978, 1984) and some data related to particular local products have been collected (Thomson, 1987). However, the effects of using nails in timber structures, and crest fixings, which have received relatively little attention overseas, need to be examined. Appropriate connection test methods have to be developed for trough fixings in timber and crest fixings in general. Other tests on the strength and flexibility of various purlin to rafter connections (Bryan and El-Dakhakhni, 1968b), which are relevant for diaphragms fastened on two sides only, are also necessary.

Although various theoretical methods of design based on simplified equations are well developed overseas, it is necessary to review their suitability for local applications; and if required, to modify or to develop appropriate solutions. Work in this direction has been attempted (Moss and Aitkin, 1981) but it is essential to include assessment of the latest developments in this field (various authors, see 18). Initially, it will be necessary to confirm the validity of the appropriate analytical approach through panel tests; particularly for applications involving crest fixings in steel structures and crest or trough fixings in timber structures. An analytical approach, if proved feasible, will overcome the shortcoming at present of design based on panel tests alone for these arrangements; as a simple, efficient and economical design tool it is very attractive in relation to the dominant nature of timber constructions in the domestic market. Finite element programmes may also be essential in investigating unusual panels or structures.

For routine design of common cladding arrangements, design tables always hold a tremendous appeal to designers and steps towards preparing such documents, after the basic approach and data are available, are well documented (Davies and Bryan, 1979) and should be pursued for New Zealand.

This constitutes the future work to establish practical design information for profiled sheet steel diaphragms in New Zealand under static loads. In view of the local need to cater for wind and strong earthquake effects, the ductility of this type of diaphragm and its behaviour under fatigue and dynamic loads also warrant special investigation.

CONCLUSIONS

In this paper, the basis of diaphragm action and overseas development are briefly reviewed. The overseas work on trough fixed cladded steel structures has been very extensive and design methods are well developed. However, investigations relevant to local practices are relatively few, i.e., those on crest fixing practices and applications of profiled sheet steel diaphragms in timber framed structures. Local products and practices have been examined and there is no reason why benefits cannot be achieved through incorporating this diaphragm action in the design. Future work to prepare useful design information is identified.

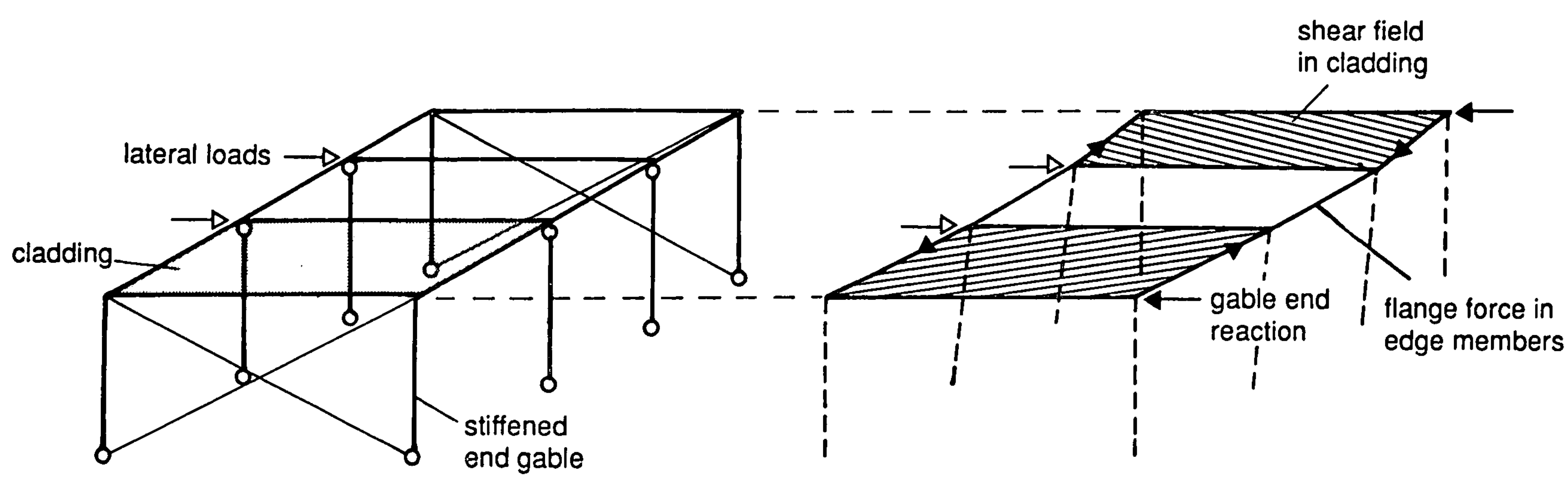

Figure 1 : Diaphragm action in a flat-roofed building with non-rigid frame.

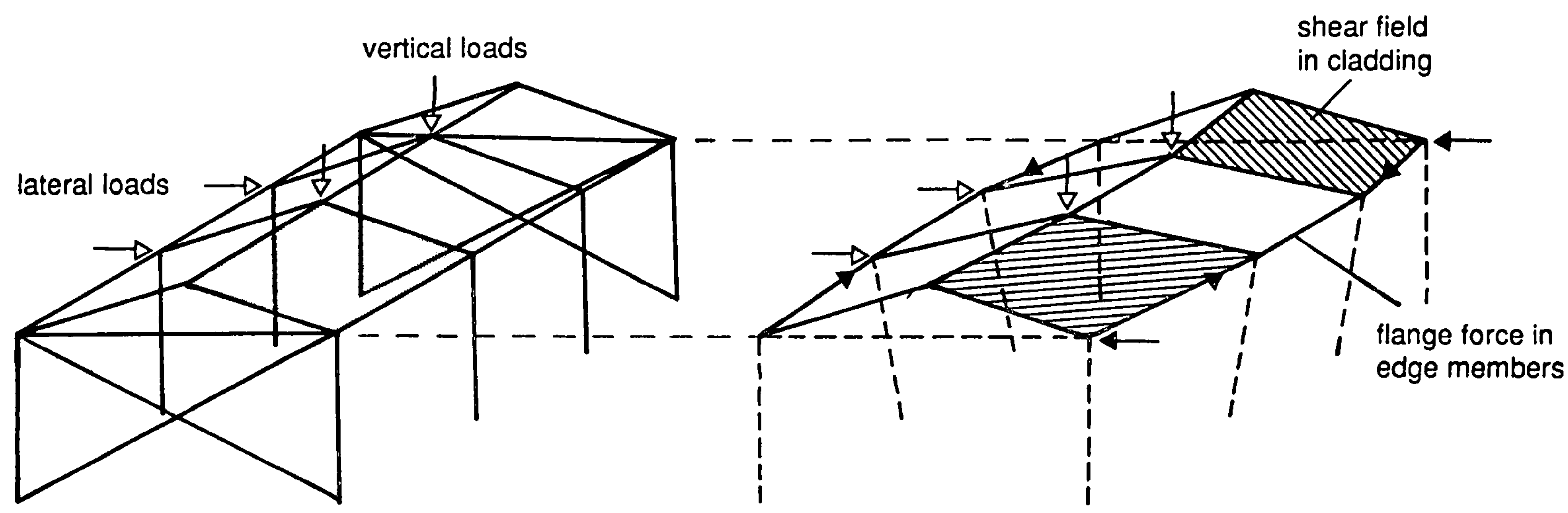

Figure 2 : Diaphragm action in a pitched-roof building.

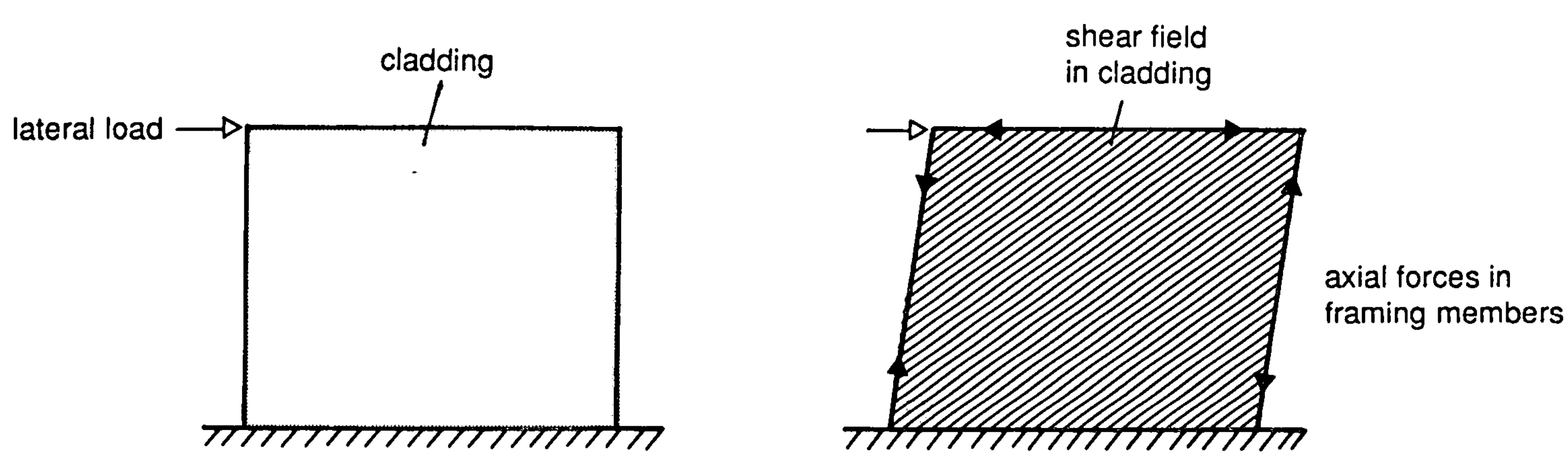

Figure 3 : Diaphragm action in a wall.

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6. Refer to bibliography: current design documents overseas - standards, codes of practice and design guides.

7. Baehre and Nyberg, 1974; Bryan, 1976; Bryan and Davies, 1981; CONSTRADO, 1973a; Davies and Bryan, 1982; European Convention for Constructional Steelwork (ECCS), 1977.

8. Refer to bibliography:

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    2. historic and supplementary technical publications:

        - diaphragms and applications in stabilising pin-jointed steel structures;

        - diaphragms and applications in stabilising timber structures.

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11. Atrek and Nilson, 1976, 1980; Davies, 1976; Eriksson, 1980; Ha, 1979; Lawrence and Sved, 1972; Nilson, 1973; Nilson and Ammar, 1974.

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    2. fasteners for profiled sheet steel diaphragms associated with timber supporting members.

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This bibliography has been prepared to perform two main functions. The first is to provide the practising engineer with a list of up-to-date documents related to the use of diaphragm action in design involving profiled sheet steel. Secondly, since the design practice of this type of diaphragm is well developed overseas, it is desirable to include background and supplementary information for use by engineers and research workers.

In line with these two purposes, the bibliography has been divided into three main sections: (1) current design documents overseas; (2) historic and supplementary technical publications; and (3) miscellaneous publications. The first section includes current publications overseas which are considered to apply directly to the design of profiled sheet steel diaphragms. The publications in the second section should prove useful to the engineer in understanding the background of the subject and to the research worker in furthering the state-of-the-art. For easy reference, the lists on work associated with steel and timber structures have been separated. The miscellaneous publications are those of a less technical nature and also on subjects of related interest.

Notes

The bibliography is concerned specifically with profiled sheet steel applications in conventional low-rise steel and timber structures and does not include the literature on light gauge steel applications in folded plate structures, hyperbolic paraboloids and cylindrical shells; nor does it include those on diaphragms of aluminium, wood and other materials.

References marked with an asterisk are identified as the more relevant documents in relation to local applications. These are held by BRANZ and will be of use to designers and research workers in this field.

Some papers appear in more than one of the categories.

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