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Diaphragm Action in Aluminium-Clad Timber-Framed Buildings

Effet de diaphragme dans les charpentes en bois revêtues de tôles d'aluminium

Membranwirkung in Gebäuden mit aluminiumverkleideter Holzkonstruktion

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SUMMARY

The results of experiments on aluminium shear diaphragms fastened to timber framing are reported. The framing system is intended to be used on roof trusses in pole-type agricultural and commercial buildings. Variables studied include connector patterns, connector types (screws and adhesives), purling size and spacing, diaphragm length, and type of loading (unidirectional and reversing). The diaphragms were of sufficient strength and stiffness to be effective im medium size buildings. Cyclic loads up to 55% of single cycle load capacity did not reduce strength. Adhesive connections were highly beneficial.

RÉSUMÉ

Cette contribution présente les résultats d'essais sur des diaphragmes de cisaillement en aluminium fixés sur des charpentes en bois. Ces systèmes porteurs sont prévus pour les toitures à fermes en treillis en bois utilisées dans les bâtiments agricoles et commerciaux. Les paramètres étudiés concernent la disposition et le type d'assemblages (vis ou colles), la dimension et l'écartement des pannes, la longueur du diaphragme et le type de chargement (dans un seul sens ou dans les deux sens). Les diaphragmes se sont révélés suffisamment résistants et rigides pour être efficaces dans les bâtiments de taille moyenne. Des cycles de charges jusqu'à 55% de la capacité statique n'ont pas eu d'influence sur la résistance ultime. Les assemblages collés ont présentés un comportement très favorable.

ZUSAMMENFASSUNG

Resultate von Versuchen an schubbelasteten Aluminium-Membranen, die auf einer Holzkonstruktion befestigt sind, werden mitgeteilt. Das Membransystem soll auf den Dachbalken von auf Stützen ruhenden Landwirtschafts- und Lagergebäuden angebracht werden. Die untersuchten Variablen sind u.a. Grösse und Abstand der Pfetten, Membranlänge und Lasttyp (in einer Richtung oder wechselnd), sowie Befestigungsanordnung und Befestigungstyp (Schrauben oder Kleber). Die Membranen hatten hinreichende Stärke und Steifigkeit für die Anwendung in mittelgrossen Gebäuden. Wechselbelastungen bis zu 55% der Kapazität für einen einfachen Lastwechsel reduzierten die Tragfähigkeit nicht. Geklebte Verbindungen erwiesen sich als besonders wirksam.

1. INTRODUCTION AND SCOPE OF STUDY

Light gage aluminum roof and exterior wall systems have been used as covering materials for timber-framed agricultural and commercial buildings for many years. This type of structure normally has trusses spanning between timber pole columns, with knee braces running from the bottom chord of the truss to the columns to provide resistance against horizontal wind action. In-plane shear forces will tend to develop in the roof of this type of building when it is loaded by wind action. The shear stiffness of the roof will be mobilized and lateral wind forces will be transferred to the ends of the building, provided that the diaphragm is properly connected to the structural framing and that the framing itself is detailed and constructed to carry the substantial edge forces that develop. This so-called diaphragm action is well-documented for steel building construction and is used in current designs.

The purpose of this study is to evaluate the performance of aluminum panels on timber framing for use as shear diaphragms on buildings. Variables studied include truss spacing, purlin spacing and size, connector patterns, type of connector (several different screws, adhesives), diaphragm length, and type of loading (single load to failure, and cyclic reversing loads to simulate wind action). The most significant results are summarized and design recommendations are presented. Additional details are given in [1], [2], and [3].

2. SPECIMEN GEOMETRY AND MATERIALS

2.1 Geometry

Shear strength and stiffness were measured by testing cantilever-type shear diaphragms as shown in Fig. 1. The strength is expressed in terms of shear loading per meter of length, where the length of the diaphragm is measured parallel to the direction of the corrugations and the applied shear load. It is known from experiments on steel diaphragms that the strength per unit length is essentially independent of length. On the other hand, shear stiffness is dependent upon diaphragm length because much of the shear deformation is produced by imperfect connections of the shear diaphragm to the edge members, particularly at the ends of the sheets. As the diaphragm is made longer, the end deformations become a smaller fraction of the total deformation and the measured shear stiffness increases. Two diaphragm lengths (3.86 and 5.69 m) were tested.

Each diaphragm was made from ribbed ALCOA aluminum Super Temper Rib panels described in 2.2 below. Three panels, each covering a 0.914 m width, were used to make a 2.743 m wide diaphragm. Two building framing geometries were simulated: (a) trusses spaced 1.22 m on center, with 38 mm by 89 mm timber purlins spanning flatwise over the top chords of the trusses at one of three different spacings (0.61 m, 0.73 m, or 0.91 m), and (b) trusses spaced 2.44 m on center, with 38 mm by 190 mm timber purlins spanning on edge.

In each system the truss chords were simulated by 38 mm by 190 mm timber members loaded on edge. Purlins were fastened to the chords with two 12d pole barn nails at each intersection. The resulting bare frames had negligible shear stiffness. Most experiments utilized the closer truss spacing (1.22 m) because diaphragms built with the wider truss spacing and purlins on edge were extremely flexible in shear.

2.2 Aluminum Panels

The ALCOA Super Temper Rib panels had measured thicknesses of the patterned sheet (Fig. 2) ranging from 0.38 to 0.41 mm, with 19 mm deep major rib corrugations. Panel width was 0.956 m to cover a space of 0.914 m. The material had a 0.2% offset yield strength of 310 MPa, an ultimate tensile strength of 365 MPa, and an elongation at failure of 7% over a 51 mm gage length.

2.3 Timber Framing

All framing members were #1 and #2 Dense Southern Yellow Pine lumber furnished by Agway from their supply normally used for farm and commercial buildings.

2.4 Fasteners

Fastener notation is shown in Fig. 1. Fasteners around the perimeter of the diaphragm are called end frame fasteners and edge frame fasteners. Purlin fasteners are screws passing through the aluminum sheet directly into the purlins; purlin sidelap fasteners are similar connectors that pass through both panels at a sidelap. Sidelap stitch fasteners were used at the purlins in some specimens. Intermediate sidelap stitch fasteners are those connectors located at sidelaps and in between purlins (specimens 10, 19, 22, 31, 32, and 36).

Drill-Kwick self-drilling ALCOA aluminum screws were used in diaphragms 1-16, 23-35, and 37-39. These fasteners are #10 with an 8 mm hex-washer-head and an aluminum/neoprene composite bonded washer for weather tightness. 25 mm long screws were used through the flat portion of the sheet and 50 mm screws were used through the high corrugated ribs; the longer screws proved to be ineffective and were not used in later specimens.

Buildex Hi-Thread TEKS screws (designation #10-16 by 25 mm hex washer head TEKS 2 Alu TRU-GRIP/h.t.) were used in diaphragms 11-22 and 36. The screw features a larger diameter thread under the head of a 16 mm across-flats hex two piece Twin-Seal washer head.

Adhesive connections were utilized in the sidelap seams in diaphragms 25, 28-30, 34, and 39. The adhesive consisted of a 6 mm diameter bead of B.F. Goodrich PL-400 construction adhesive. One specimen, #40, had continuous adhesive connections between the purlins and the sheeting, in addition to adhesive connections at the sidelap seams.

3. TEST PROCEDURES AND DEFINITIONS

The cantilever test method described in [4] was used to evaluate shear strength and stiffness of each diaphragm. Shearing force was applied with a hand-operated mechanical jack in increments of 445 N. The net shearing deformation used in calculating shear stiffness was corrected for support movements in accordance with the method suggested in [4]. Another very important deformation measured in each test was the sidelap seam slip; it is an excellent indicator of shear stiffness as well as a good signal of impending difficulties in maintaining strength as load is increased since the full shear load in the diaphragm must be transmitted from one panel to the next across each of the two sidelap seams in the three-panel diaphragm.

The effective shear stiffness G for use in design is defined as G' = the load P at 40% of P_{ult} divided by Δ_s, where Δ_s' is the deflection measured at a load of $0.4P_{ult}$ minus the calculated bending deflection at the free end of the cantilever diaphragm, as specified in [4]. The bending deflection is factored out to eliminate the dependence of test results on the properties (plan dimensions, perimeter member areas and modulus) of the cantilever test specimen.

4. EXPERIMENTAL RESULTS

4.1 Introduction

Many connector combinations were used in the overall test program to find the optimal arrangement of connectors; hence many test results are not significant. Details of all tests are given in [1], [2], and [3]. Results here are limited to three diaphragms loaded unidirectionally to failure and one diaphragm loaded with reversing shear to simulate wind effects. Comparisons between various tests and

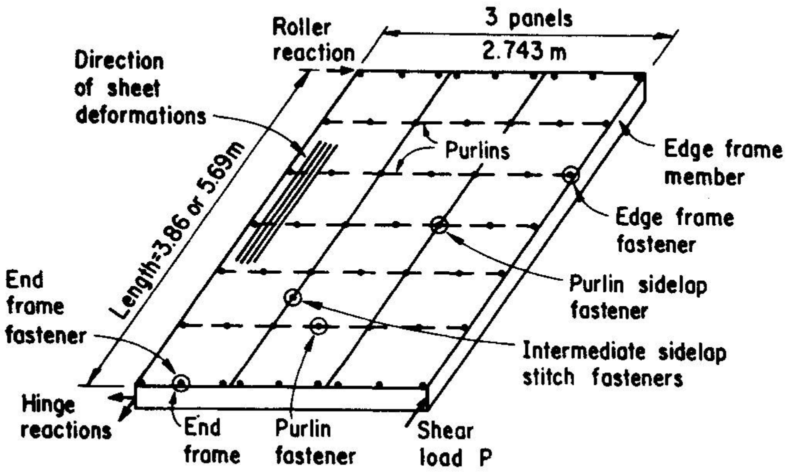


Fig. 1 — Diaphragm Geometry and Connector Geometry

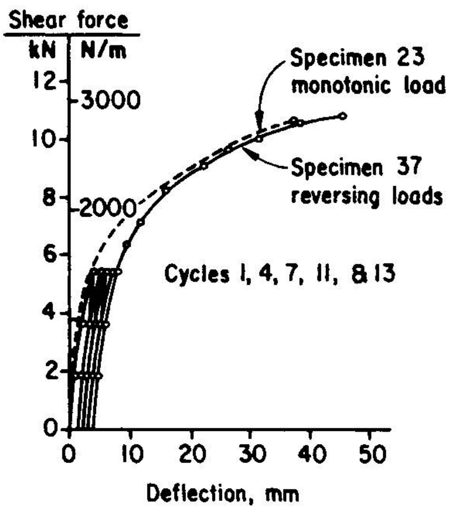


Fig. 4 — Effect of Reversing Loads

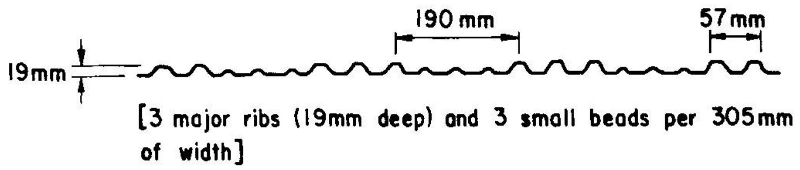


Fig. 2 — Panel Dimensions

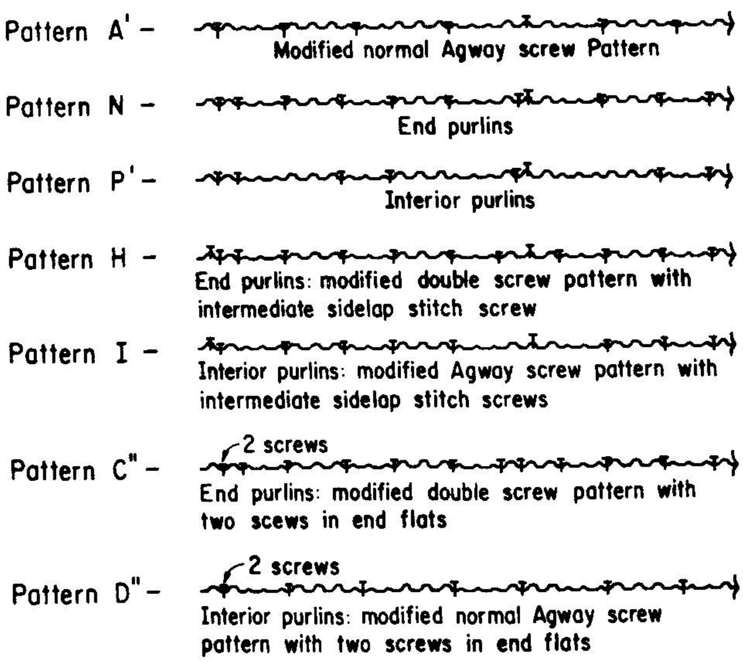
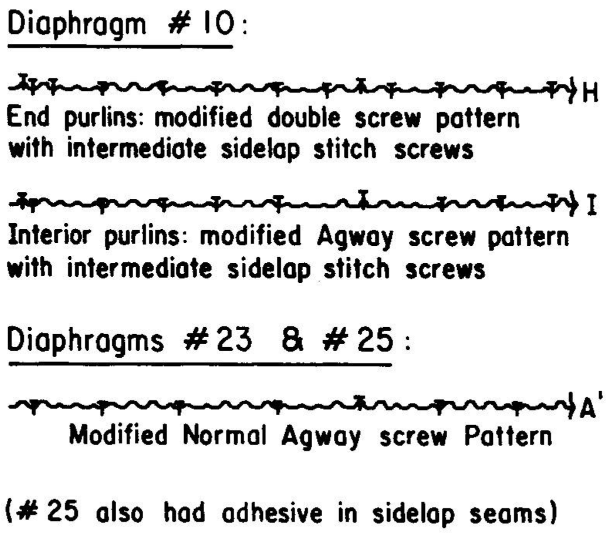
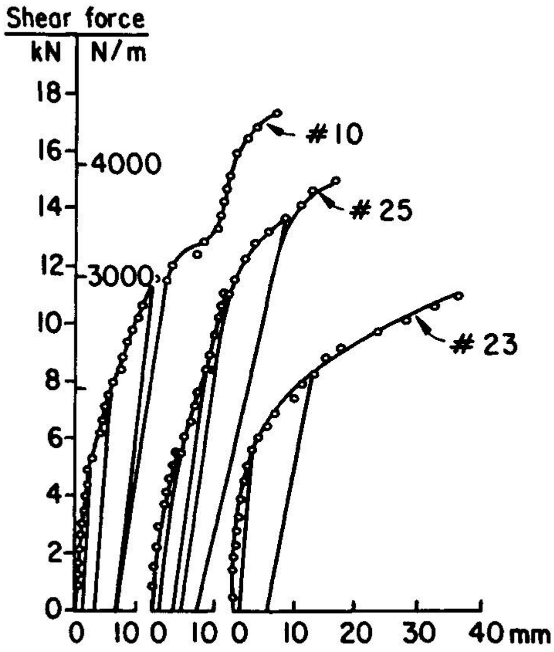


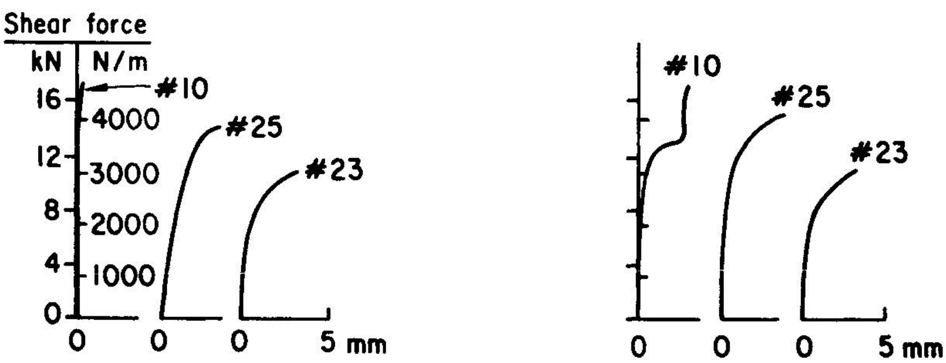
Fig. 5 — Screw Patterns for Recommended Designs



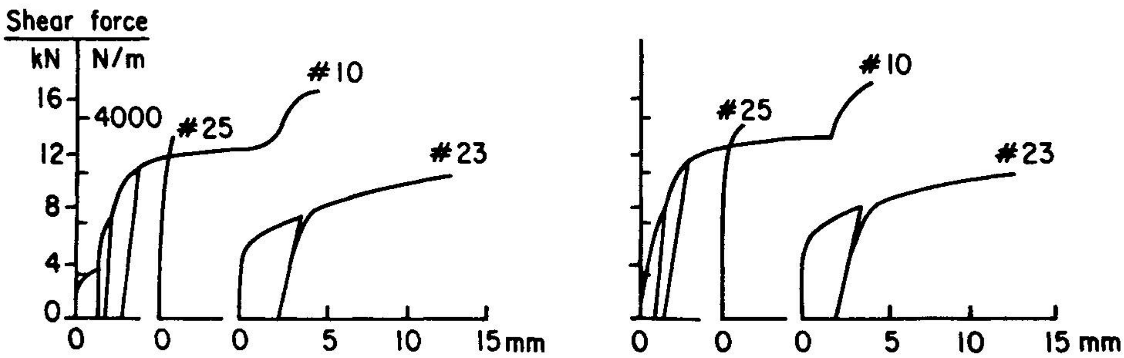
(a) Connector patterns



(b) Shear vs. deflection



(c) Net slip along loaded edge member, mm



(d) Sidelap seam slip, mm

Fig. 3 — Performance of Typical Diaphragms

evaluation of the influence of test parameters are given in Chapter 5.

4.2 Diaphragms Loaded to Failure with a Single Load

Typical results are given for three specimens with capacities suitable for design shears of 1680, 2260, 2700 N/m, respectively. These design shear capacities are appropriate for small to medium size buildings. Each of these diaphragms had a truss spacing = 1.22 m and a purlin spacing = 0.61 m.

4.2.1 Minimal Screw Pattern (Specimen 23)

This diaphragm had 91 screws with all edge screws placed in the valley between ribs as shown in Fig. 3a. The diaphragm exhibited buckling-type deformations in the central flat areas of the panels, along with twisting of the adjacent ribs, at a load of 1600 N/m. Net deflection, slip along the loaded edge member, and sidelap seam slip are plotted in Figs. 3b, 3c, and 3d, respectively. Failure was initiated by tipping of the sidelap seam screws of up to 45° with associated sheet tearing around the screws. The specimen failed at 2760 N/m by fracture of several sidelap seam screws at the purlins; G′ was 1.20 kN/mm.

The diaphragm exhibited nearly elastic behavior up to a load of about 1170 N/m with less than 2.5 mm residual deflection upon unloading from 1460 N/m; there was virtually no sidelap seam slip at 1460 N/m shear load. Sidelap seam slip increased rather sharply at higher loads and residual seam slip was nearly 6 mm after unloading from 2190 N/m, as shown in Fig. 3b. Interior panel deformations were completely elastic and fully recoverable up to loads of 2190 N/m.

A duplicate specimen showed essentially identical behavior. As confirmed by other tests, the only way to reduce the sidelap seam lip at higher load levels was to either add intermediate stitch screws in the sidelap seams or to place adhesive in the sidelap seams.

4.2.2 Minimal Screw Pattern Plus Adhesive in Sidelap Seams (Specimen 25)

This diaphragm was identical to Specimen 23 discussed in 4.2.1 above except for the addition of a 6 mm continuous bead of BFG PL-400 construction adhesive in the sidelap seams. The adhesive eliminated the sidelap seam as the critical link in strength and stiffness of the diaphragm. As shown in Fig. 3d, sidelap seam slip was an order of magnitude smaller than in the previous specimen and residual slips remained low even when unloading from load levels up to 2800 N/m.

The diaphragm showed buckling-type deformations in the central flats of each panel at a load of approximately 1600 N/m. It failed at 3810 N/m as a result of severe distortion of the panels and resultant runaway deflections. The shear stiffness G′ was 0.74 kN/mm, lower than for Specimen 23. This apparent anomoly is attributed to great increase in load capacity of the diaphragm and hence the proportionally larger displacement at 40% of the ultimate load.

4.2.3 Additional Screws at Purlins Plus Intermediate Stitch Screws (Specimen 10)

This diaphragm used 150 screws in the patterns shown in Fig. 3a. End purlins had double screw patterns in the flats to help control deformations at the ends of the panels. Intermediate stitch screws were used between the purlins in both sidelap seams. As shown in Fig. 3b, this diaphragm design had an extremely high initial stiffness and a high shear stiffness G′ (1.08 kN/mm). The presence of the intermediate stitch screws forced the failure to occur by shear-off of the edge frame screws at a load of 4490 N/m. The observed sharp arresting of sidelap seam slip at a load of 3650 N/m (Fig. 3d) suggests that the stitch screws became effective only at high load levels. As ultimate load was approached, the stitch screws tilted and eventually broke the seal between the panel and the neoprene washer under the screw head.

4.3 Diaphragms Subjected to Reversing Shear Loads

Four diaphragms (Specimens 16, 37, 38, and 39) were subjected to reversing shear load tests to better simulate the actual loading history that a roof diaphragm will encounter during its lifetime. The objective of these experiments was to study potential degradation in stiffness and strength from the cyclic loading. Behavior of Specimen 37, which was identical in design to Specimen 23 discussed in 4.2.1 above, is summarized in Fig. 4. Load-deflection behavior is plotted for loads in one direction only for selected cycles. It is apparent that there is substantial cumulative gain in diaphragm deflection. However, the tangent stiffness at any load level does not change significantly from the monotonically loaded specimen, and strength after cycling is unchanged. Other specimens confirm this behavior.

5. INFLUENCE OF MAIN DESIGN PARAMETERS ON DIAPHRAGM PERFORMANCE

The influence of the main design parameters on diaphragm performance is evaluated in the chapter. Included are: purlin spacing, truss spacing, use of adhesive in sidelap seams, reversing loads, connector patterns, and length effect.

5.1 Purlin Spacing

Three specimens (26,33,11) made without adhesives showed that increasing the purlin spacing from 0.61 m to 0.73 m reduced strength by 10%, and that a further increase to 0.91 m reduced strength an additional 8%. Shear-slip response up to loads of nearly 1500 N/m was not affected by purlin spacing, nor was G . Three specimens (29,30,34) with adhesive in sidelap seams showed that strength was essentially independent of purlin spacing because failure was in the panel rather than in the connectors.

5.2 Truss Spacing

Decreasing the truss spacing from 1.22 m (Spec. 23,24) to 0.81 m (Spec. 35) had little effect on strength and produced a small increase in stiffness.

5.3 Use of Adhesive in Sidelap Seams

In addition to Specimens 23 and 25, three other pairs of diaphragms (26 and 29, 33 and 34, 38 and 39) were built with and without adhesive in the sidelap seams. The sidelap seam adhesive connection produced the most dramatic change in behavior of any of the parameters studied. It drastically reduced the sidelap seam slip at high load levels (see Fig. 3d), eliminating the sidelap seam as a failure path in the diaphragm, and increasing strength from 20% to 40%. The strength of a 6 mm bead of this adhesive stabilized at 20 N/mm after 7 days of curing at room temperature.

5.4 Reversing Loads

Three pairs of tests (23 and 37, 26 and 38, 29 and 39), in which the second specimen of each pair was subjected to 13 cycles of reversing loads, showed that the behavior during the last cycle of loading was very similar to that of the monotonically loaded specimen except for the residual deflections of 2.5 to 5 mm that existed after 13 cycles of load. Secant stiffnesses based on total deflections at $0.4P_{ult}$ indicated that the cycled specimens without adhesive sidelap seams were about 1/3 as stiff as uncycled specimens; Specimen 39 made with adhesive sidelap seams retained about 60% of the secant stiffness of the uncycled diaphragm.

5.5 Connector Patterns

Fastener patterns for several different levels of strength are given for a truss spacing of 1.22 m with purlins spaced at 0.61 m and nailed flat against the top chord of the trusses. Permissible design loads are taken as 60% of the ultimate load capacity for design conditions controlled by wind loading. Connector patterns are summarized in Fig. 5.

Shear capacity N/m	Connector pattern	No. of screws	Adhesive	Stiffness G′ kN/mm
1680	A′	91	No	0.89 kN/mm
2260	N′,P′ + S.S.*	123	No	0.88 k
2700	H,I + S.S.*	150	No	1.07
2260	A′	91	Yes	0.74
2550	C′′, D′′	123	Yes	1.05

*S.S. = stitch screws

Higher capacities could be achieved in diphragms made with adhesives by using more screws, and substantially higher capacities (certainly up to 3700 N/m) could be reached by using adhesives to fasten the panels to the purlins. Research is needed to assess performance of adhesives over the lifetime of a structure, where they would be subjected to thermal effects and aging.

5.6 Length Effect

The use of the length effect equation given in [4] was verified with two pairs of specimens of different lengths. Use of this equation requires experimental determination of the factor K_2, which depends upon the diaphragm cross-sectional shape and the end fastener configuration.

6. CONCLUSIONS

Diaphragms made of aluminum panels and timber framing have sufficient strength and stiffness for use as roof shear diaphragms in medium size farm and industrial buildings, provided the timber framing is designed to carry the tensile forces developed by diaphragm action. Sidelap seams are critical in determining response to shear loads, and it is necessary to use either intermediate stitch screws at an average spacing of about 0.3 m, or adhesives. Screws at the ends of purlins should be located in the low flat areas of the panels rather than being placed through the high ribs. Purlin spacing had little effect on performance, provided sufficient intermediate stitch screws were used. Shear stiffness G′ varied little with different connector patterns, being quite close to 0.9 kN/mm for 4 m long diaphragms. Reversing loads of about 55% of single cycle strength can be carried safely.

7. ACKNOWLEDGEMENTS

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