Study of Thin-Walled Metal Building Roof Systems Using Scale Models

Etude des toitures métalliques à parois minces par l'utilisation de modèles réduits

Modellversuche an dünnwandigen Metalldachsystemen

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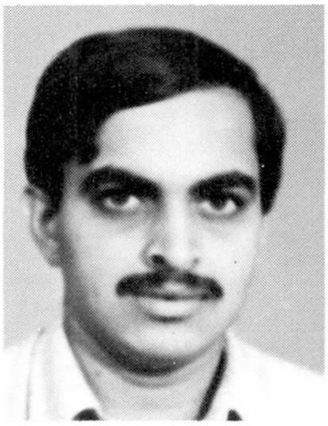

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SUMMARY
This paper presents the results of an extensive investigation on the use of quarter scale models to study the behavior of thru-fastener, metal building roof systems supported by Z-purlins and subjected to gravity loading. The objective of the study was to develop and verify methods for scale modeling of such systems. Experimental results are compared to analytical predictions and identical full-scale tests. Conclusions are made concerning the applicability of scale models for thin-walled metal structures research.

RÉSUMÉ
Cet article présente les résultats d'une enquête approfondie concernant l'utilisation des modèles à l'échelle un:quatre, pour étudier le comportement des toitures métalliques supportées par des pannes en tôle mince en forme de Z et soumises à des charges de gravité. Le but de cette étude était de développer des méthodes de modèlisation pour ce genre de structures, et de les vérifier. Les résultats expérimentaux sont comparés à ceux d'essais en vraie grandeur et à des prévisions analytiques. Les conclusions données concernant l'applicabilité du modèle réduit à l'étude expérimentale des structures en tôle métallique à parois minces.

ZUSAMMENFASSUNG
Die Ergebnisse einer umfassenden Untersuchung über die Anwendung von Modellen im Massstab 1:4 zum Studium des Verhaltens von Metalldachsystemen mit Z-Pfetten und unter Schwerkrafteinfluss werden vorgestellt. Das Ziel der Untersuchung war, Methoden für das massstabsgerechte Modellieren solcher Systeme zu entwickeln und zu prüfen. Experimentelle Ergebnisse werden mit analytischen Vorhersagen und den Resultaten identischer Tests an Tragwerken im Massstab 1:1 verglichen. Folgerungen über die Anwendbarkeit von massstäblichen Modellen für Untersuchungen von dünnwandigen Metalltragwerken werden gezogen.

1. INTRODUCTION

An extensive investigation on the use of quarter scale models to study the behavior of thru-fastener, metal building roof systems supported by Z-purlins and subjected to gravity loading is summarized here. A complete description of the research is found in Ref. [1]. The principal objective of the study was to develop and verify methods for scale modeling of such roof systems. Special fabrication, assembly and testing techniques were used to construct and test the model systems, which ranged in size from single span, two purlin line to three continuous span, six purlin line systems. Effects of different deck-to -purlin fastening systems and deck diaphragm stiffness were also studied.

Results from forty-three model tests are summarized and compared to some identical prototype tests and to analytical predictions. Comparisons include failure mode, failure load, vertical deflections and magnitude of restraint forces. Results from tests where edge stiffener orientation was varied are also presented herein.

2. MODELING AND METHODOLOGY

2.1 Z-Purlins

The Z-purlins were fabricated using 24 gage (0.6 mm) steel sheet material having a nominal yield stress of 345 MPa. The sheet was first sheared to the required width (developed length of the purlin cross-section) and then bent into a Z-shape without edge stiffeners using a press brake. The essential steps are shown in Figure 1. The edge stiffener was bent to shape by hammering against a mandrel machined from a steel block. The edge stiffener formed by this method was found to be accurate in length and in orientation and free of local distortions. Purlin depths ranged from 152 mm to 305 mm. The span length for all tests was 1.52 m. Standard ASTM tensile test coupons were cut from virgin sheet material and tested. The average measured yield stress was 357 MPa.

2.2 Roof Deck and Fasteners

Four types of panels were used in the test program. A corrugated fiber glass panel was used in one test. The system failed due to tearing of the panel at fastener locations and this panel type was discarded. Either commercially available corrugated aluminum panels or corrugated steel panels were used in all other tests. A steel "sine wave" sheet having 13 mm deep corrugations was used in most tests.

Two types of fasteners were used to attach panels to the purlin flanges: self-drilling fasteners or machine screws and nuts. All panels were fastened to the purlin flange in every corrugation valley. For multiple purlin tests, the panel-to-panel connection (sidelap fastening) was made using machine screws spaced at 150 mm on center.

Initially, shear (diaphragm) stiffness of the deck and the type of fasteners used were thought to effect the behavior of the system. The panels and the fasteners could not be accurately scaled because of the availability of material and other limitations. Hence, it was decided to conduct tests with combinations of several commercially available panels and fasteners to study the effect of these components on the behavior of the system.

Two tests of two purlin line, single span systems, one with corrugated steel panels and the other with corrugated aluminum panels, were conducted. The failure mode for both tests was local buckling of the compression edge

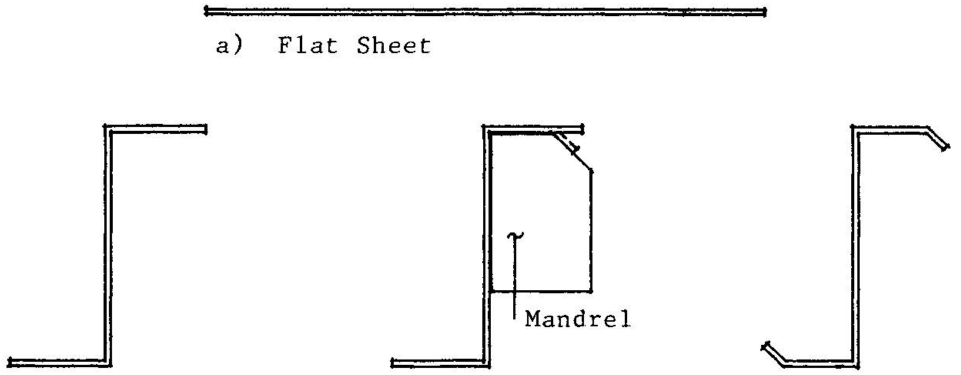


Fig. 1 Z-Purlin Fabrication Procedure

stiffener/flange/web near midspan. The failure load for the former test was 1.12 kN/m and the latter test, 1.04 kN/m. Forces in dynamometers placed at the supports and used to stabilize the system were 18.3% of applied working load for the steel panel test and 18.7% for the aluminum panel test. The corresponding percentages at failure were 19.5% and 19.2%. Since the diaphragm stiffnesses of the two systems were considerably different, it was decided to use steel panels in all further testing for economic reasons.

Analyses to determine restraint forces in systems with widely varying panel shear stiffnesses were conducted by Elhouar [2]. He found that panel stiffness has little effect on roof system behavior if the shear stiffness is greater than 1.82 kN/m. (A typical metal building thru fastener roof system exhibits a shear stiffness in excess of 1.22 kN/m). A shear stiffness test using the selected steel panel was conducted and was found to be 3.04 kN/m.

The effect on the behavior of the system due to the fastener type used to attach the selected steel panel to the purlin was also studied. Two identical, single span, two purlin line tests were conducted; one using machine bolts and the other using self-drilling fasteners.

Again, the failure modes for the two tests were identical. The failure loads were 1.12 kN/m and 1.16kN/m and restraint forces were 18.3% and 17.9% of the applied working load for the machine bolted and self-drilling fastenered systems, respectively. Since the test results showed that the effect of fastener type was not significant, machine bolts and nuts were used for most test setups because of ease of fabrication.

2.3 Test Setup and Testing Procedures

The test setups consisted of simulated building rafters and the purlin/deck assemblies. Support conditions along a purlin line consisted of rollers except at one location where a simulated pinned support was used. The pinned support consisted of a roller between two plates with a groove in each plate. One plate was attached to the bottom flange of the purlin; the second plate was attached to the rafter. The roller support was similar except the plates were flat allowing free movement of the roller.

Restraint braces were supplied at the rafter lines, at midspan or at span one-third points in the test setups. These braces were fabricated from small diameter, steel hydraulic brake line normally used in automobiles. Universal joints were used at each end to eliminate rotational restraint at the connection. Selected braces were strain gaged and calibrated for use as dynamometers to measure restraint forces.

Instrumentation consisted of the dynamometers and linear displacement transducers to measure vertical deflections and horizontal displacements of the top and bottom purlin flanges. For the two purlin line tests, gravity loading was applied using clay brick masonry units. A small suction box was constructed to test multiple purlin line assemblies.

3. EXPERIMENTAL RESULTS

3.1 Program Objectives and Test Matrix

Tests were conducted to:

(1) Verify that scale models can be used to accurately study the behavior of full scale roof systems.

(2) To calibrate a proposed computer model to predict restraint forces.

(3) To study the effect of edge stiffener angle on purlin strength.

To accomplish the above, a total of 43 model tests and twelve full scale tests were conducted. All tests were conducted with the purlin flanges facing in the same direction. Restraint braces were provided at the rafter lines, at the midspans or at the one-third span locations. In the following discussion, the restraint braces at the rafter locations will be referred to as torsional braces.

3.2 Comparison with Full Scale Test Results

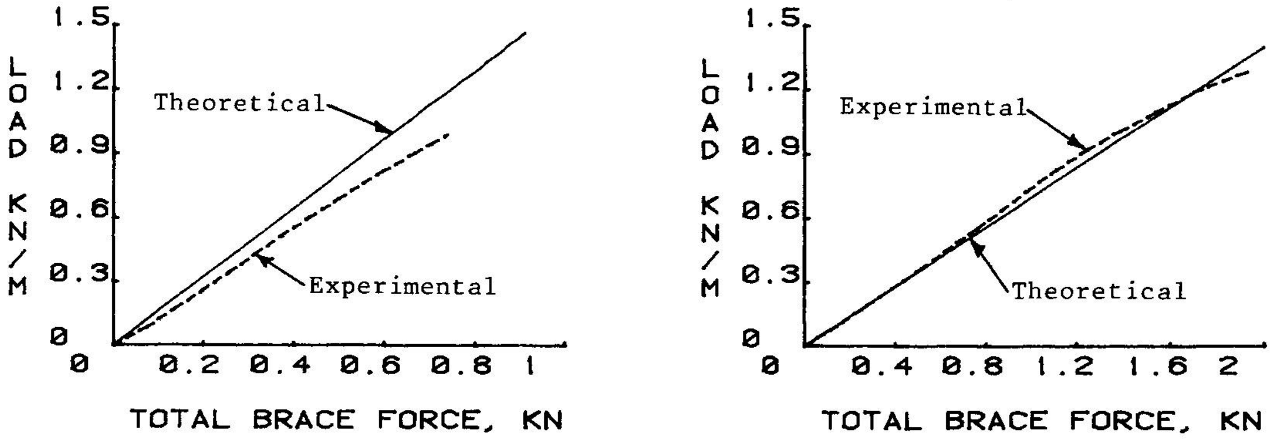
The failure mode for all the full scale and model tests was local edge stiffener/flange/web buckling near midspan in all single span and some multi-span tests or near the exterior end of the lapped portion in continuous three span tests. The shape of the locally buckled purlins was identical in all tests. In both the model and prototype tests, measured vertical deflections were linear with respect to loading, but exceeded predictions, using standard strength of material or stiffness analysis techniques, by approximately 15% until near failure when the deflections rapidly increased.

Experimental failure loads for 34 single span tests were compared to predicted failure loads based on cross-section strength calculated using local buckling criteria in the current AISI specification [3]. The average predicted-to-failure load ratio was 1.069 with a standard deviation of 0.087. A similar study for 85 full scale tests found this ratio to be 1.141 with a standard deviation of 0.199 [4].

3.3 Comparison with Predicted Restraint Forces

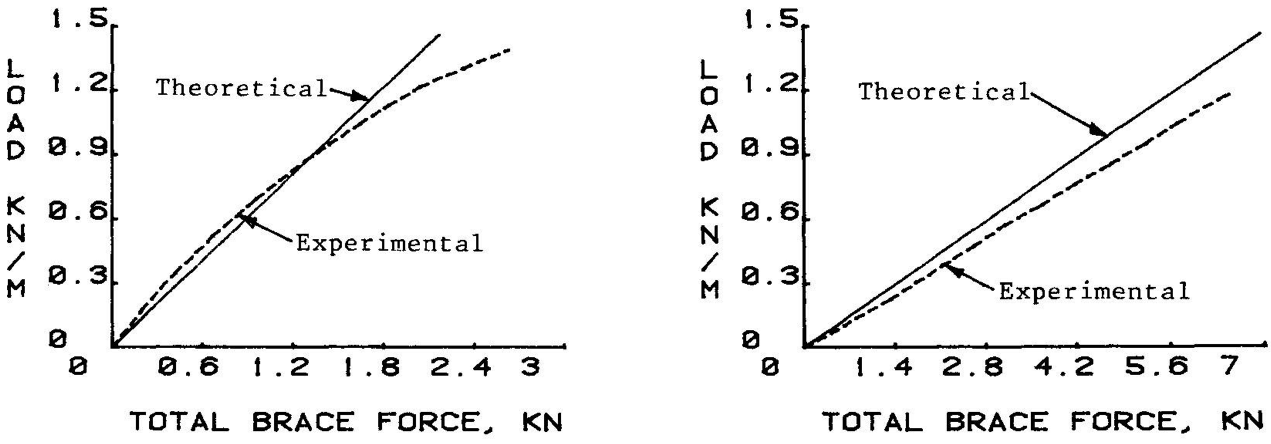
In a companion study [2,4], a direct stiffness, computer based model was developed to predict restraint forces in single or multiple span, multiple purlin line, Z-purlin supported, gravity loaded roof systems. Full scale tests were initially used to calibrate the model. Sixteen quarter scale tests were then conducted to further verify the adequacy of the analytical model. The test matrix consisted of two and six purlin line, single and three continuous span configurations. Each of the previously described restraint bracing configurations were used with each of the purlin line/span configurations.

Figure 2 shows typical applied load versus restraint force results. In these plots the solid line represents the predicted relationship and the dashed line, the experimentally measured relationship. The results shown in Figure 2(a) are from a two purlin line, single span test with restrait braces at the purlin ends (torsional braces). Similar results are shown in Figure 2(b) for a



a) Two Purlin Line, Simple Span, Torsional Restraints

b) Six Purlin Line, Simple Span, Torsional Restraints



c) Two Purlin Line, Three Spans, Midspan Restraints

d) Six Purlin Line, Three Spans, Third Point Restraints

Fig.2 Applied Load Versus Brace Force Relationships

six purlin line, single span, torsional brace test. Figure 2(c) shows results for a two purlin line, three continuous spans test with restraints at each midspan. Finally, results are shown in Figure 2(d) for a six purlin line, three continuous spans configuration with third point restraint braces.

3.4 Effect of Edge Stiffener Angle

A series of tests was conducted to study the effect of edge stiffener orientation on the ultimate flexural strength of Z-purlins. Seven, two purlin line, single span tests were conducted using identical purlins except for edge stiffener orientation. The angle of orientation from the horizontal of the edge stiffeners was varied in 15° increments from 30° to 90°.

The ratios of the experimental ultimate loads W_u to the predicted ultimate loads W_p are shown in Table 1. The ratio increased from 78.1% for the 30° lip angle test to 97.5% for the 75° lip angle test. For the three 90° lip angle test, the results were 92.2%, 86.9% and 90.2%.

Lip Angle	W_u/W_p %	% Brace Force at Working Load		% Brace Force at Failure	
		Predicted	Measured	Predicted	Measured
30°	78.1	22.60	20.9	22.60	21.2
45°	90.3	21.70	18.3	21.70	19.5
60°	95.1	22.00	18.1	22.00	18.4
75°	97.5	21.30	17.6	21.30	17.2
90°	92.2	20.10	20.1	20.10	21.1
90°	86.9	20.27	28.6	20.27	31.0
90°	90.2	21.72	18.3	21.72	19.5

W_p = Predicted Ultimate Load

W_u = Failure Load

Table 1 Summary of Results for Lip Angle Test Series

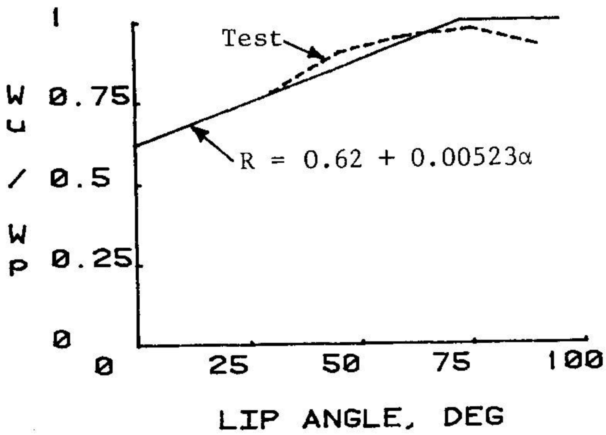


Fig. 3 Strength Ratio versus Lip Angle

A plot of W_u/W_p versus lip angle is found in Figure 3. The solid line is a prediction equation developed from prototype tests [5]

$$R = 0.62 + 0.00523\alpha \quad (1)$$

where R = reduction due to edge stiffener inclination and α = orientation angle measured from the horizontal, in degrees.

Restraint forces were both measured and predicted for the tests. Except for the tests using the 90° edge stiffener inclination, the measured restraint force was slightly less than predicted as seen from Table 1. For one of the 90° tests, the measured forces were considerably greater than predicted.

4. CONCLUSIONS

The results of the study reported here show that cold-formed structural members can be effectively studied using quarter scale models. For the thru fastener, metal building type roof systems studied, it was found that the roof deck and fastener systems can be modeled using commercially available materials and do not have to be accurately scaled. Full scale and model test results, including failure mode and failure load, were found to compare very well when the typical scatter of data found in thin-walled structural research is considered.

Evaluation of costs, effort, loading mechanisms, test setups and other variables shows that model based research of cold-formed structures is a desirable alternative to full scale testing.

5. ACKNOWLEDGEMENTS

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