Development and ultimate strength test of new steel gable roof structure

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Development and Ultimate Strength Test of New Steel Gable Roof Structure

Développement et essai de résistance ultime d'un nouveau type de fermes métalliques pour toit à deux pans

Entwicklung und Bruchfestigkeitsprüfung einer neuen Giebeldach-Stahlkonstruktion
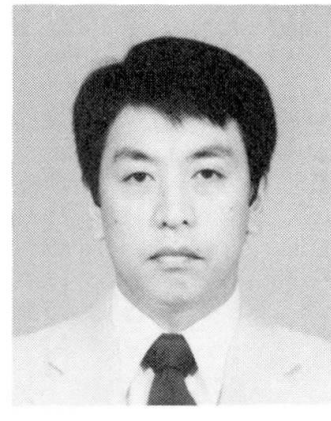
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SUMMARY

This text is a report on a recently developed steel gable roof structure designed to simplify the framing process, shorten the construction time and, by reducing weight, cut down on cost. Especially with regard to the planning of the members and frameworks, expectations are high for improvements in yield strength and deformation capacity brought about by the use of these new main and secondary members. Large-scale tests are now under way to confirm the anticipated results.

RÉSUMÉ

Le présent texte concerne le développement de nouvelles fermes métalliques pour toit à deux pans, conçues pour simplifier le procédé de montage, réduire la durée de construction et diminuer le prix de revient en minimisant le poids. En particulier, la conception des éléments et de l'ossature devrait permettre une amélioration de la résistance ultime et de la capacité de déformation lors de l'utilisation de ces nouveaux éléments principaux et secondaires. Des essais à grande échelle sont en cours pour confirmer les résultats prévus.

ZUSAMMENFASSUNG

Die vorliegende Arbeit berichtet über eine neuentwickelte Giebeldach-Stahlkonstruktion, mit dem Ziel, die Entwurfsbearbeitung zu vereinfachen, die Bauzeit zu verkürzen und die Baukosten durch Gewichtsverringerung zu senken. Besonders in Bezug auf den Entwurf der Bauteile und des Rahmens sind die Erwartungen hoch, was die Verbesserung der Fliesslast und des Verformungsvermögens bei Ausnutzung der Nebenbauteile, wie z.B. Fertigbauteile, betrifft. Versuche im Massstab 1:1 sollen die erwarteten Resultate bestätigen.

1. Introduction

Many of the gable roof steel frames used for factory buildings, warehouses, etc. consist of gabled plane frames arranged side by side. In developing these frames, major emphasis is placed on simplification of the steel frame production process, reduction of work time, and cost cutting by reduction of the frame weight. Under such circumstances, the type of main frame used and the design and arrangement of secondary members to improve the ultimate strength and deformation capacity of the main frame members are important considerations. This paper outlines a newly developed system frame which employs thin-walled members, and presents the results of an ultimate strength test conducted on the structure and its members.

2. Outline of the New System Frame

The major points in the development of the new system frame were to improve the main frame member production process and to integrate cross beams in the ridge direction with the siding.

1) Formation of Main Frame Members by Special Process

With a gable roof frame fixed to column base pins, the corner knee member is generally subject to substantial bending moment due to vertical loads (dead load, live load, etc.) and horizontal loads (earthquakes, winds, etc.). In terms of stress, therefore, members of non-uniform section which have sufficient bending rigidity at the corner knees are effective. The problem is how to form such members efficiently. For the new system frame, rolled H steel was cut and bent into members of non-uniform sections as illustrated in Fig. 1. The cross-sectional shape of the members of these non-uniform sections was determined such that, in the column member, the joint between the uniform and non-uniform sections and the vertex of the corner knee member reach their yield moments at almost the same time.

2) Integration of Special-Shaped, Cold-Formed Member with Siding

In order to secure the ultimate strength and deformation capacity required of a frame and to use steel products economically, it is important to ensure that the individual members of the frame fully display their capacities. For the new system frame, a newly developed cold formed channel steel of special shape is used for the main frame cross beam in the ridge direction. In addition, a special metal is used to integrate this cross beam with the roofing members, external walls, and other siding members, so as to produce a sort of stress skin effect. By so doing, the rigidity, ultimate strength, and deformation capacity required of the frame are secured by the interaction of the main frame, secondary members, and siding members, In concrete terms, the frame is set up as shown in Fig. 2. In the new system frame, an unequal leg channel steel with intermediate stiffener is used as the cross beam, which is connected to the roofing members by Type A metals provided at 50 cm intervals. In addition, a Type B metal is provided at a position corresponding to the bracing point for buckling to transmit the bracing force on the channel steel to the roofing member in the form of a couple of forces, enabling the bending rigidity of the roofing member to hold back the out-of-plane deformation which accompanies twisting. In designing the cross beam, the interval between Type B metals was used as the buckling length. As a result, it has become possible to design a simple, rational frame which dose not require the sub-beams and stud members used with conventional frames. The new design has reduced the frame weight by 15 to 20%.

3. Strength Test of Cold Formed Cross Beam

3.1 Outline of Strength Test

This test is a bending strength test conducted on the cross beam to measure the effect of integrating the cross beam with the roofing member which serves as a bracing member for lateral buckling.

In the new system frame, the roofing members are connected via metals to a cold formed channel steel used as the beam in ridge direction which connects the main frames. When the upper frange of the channel steel to which the roofing members are connected is subjected to compression, the out-of-plane deformation of the flange is completely held back by ordinary (Type A) metals provided at intervals of 50 cm. However, when a wind load is applied from below, the lower flange of the channel steel is subjected to compression. In this case, the buckling bracing effect of the roofing members connected to the upper flange (tension flange) is uncertain. In the new system frame, in particular, the lateral buckling bracing force on the compression flange is transmitted in the form of a couple of forces to the roofing members connected to the tension flange via special-shaped (Type B) metals, so as to enable the strength and rigidity of the roofing members to hold back the out-of-plane deformation which accompanies twisting of the compression flange. It is, therefore, necessary to experimentally confirm that the special-shaped metal has sufficient strength and rigidity as the bracing point for lateral buckling and that the roofing members have sufficient capacity as bracing members.
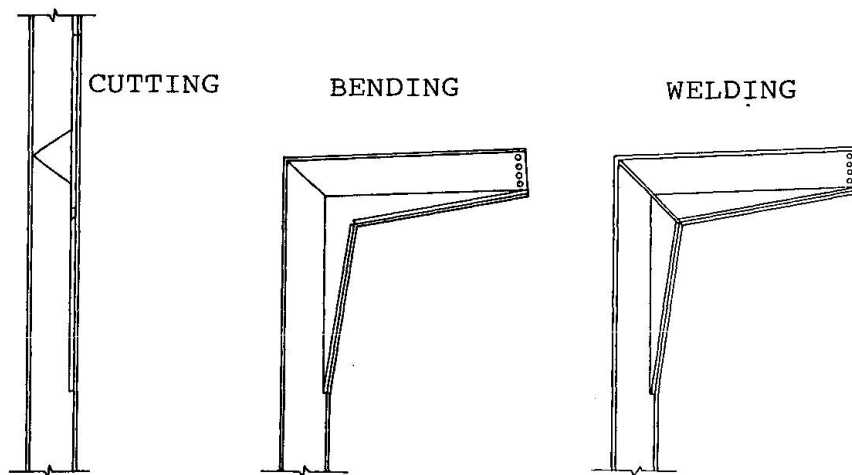

CUTTING   BENDING   WELDING

Fig.1 Formation of Main Frame Members

ROOFING MEMBER — COUPLE OF FORCE

SPECIAL METAL
(B-TYPE)

ORDINARY METAL
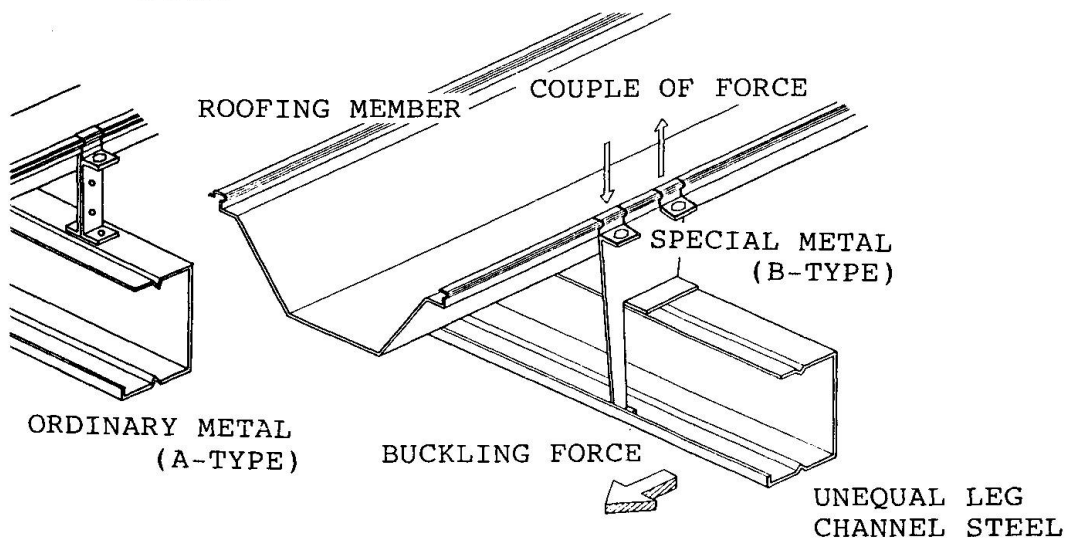(A-TYPE)   BUCKLING FORCE

UNEQUAL LEG
CHANNEL STEEL

Fig.2 System of Channel Steel and Roofing

The parameters used for the testing were the direction in which a bending load is applied and the position of the special-shaped (Type B) metal to hold back lateral buckling deformation. A total of five different test pieces were used. C-1 is a cold formed channel steel without roofing members. C-2 is a cold formed channel steel provided with ordinary metals at intervals of 50 cm and connected with roofing members. C-3 has one special-shaped (Type B) metal at the center of a cold formed channel steel. C-4 has two Type B metals at points which divide the channel steel beam into three equal sections. C-5 is the same as C-3, except that the load is applied from the opposite direction. The test pieces are outlined in Table 1. The test was conducted in the manner illustrated in Fig. 3. The test pieces were subject to equal moment. Each test piece was pinned at both ends in the strong axis and was fixed in the weaks axis to hold back end warping.

3.2 Test Results

Fig.4 shows a load-deformation curve obtained as a result of the test. The load applied was yield moment M_y, and the deformation was made dimensionless by δ_y corresponding to M_y.

With C-1 having no roofing member, torsional deformation began to occur in the initial stage of application of load. Compared with other test pieces provided with roofing members, C-1 showed lower elastic rigidity, its ultimate strength being about $0.76M_y$. C-2, which was prepared by welding ordinary (Type A) metals to a channel steel at intervals of 50 cm and connecting roofing members thereto, showed higher initial rigidity than C-1, comparable to the rigidity around the principal axis. With C-2, torsional deformation became conspicuous when the load reached about $0.90M_y$. After the ultimate strength of $0.97M_y$ was reached, C-2 showed a sharp decline in strength.

C-3, provided with roofing members in the same manner as C-2 and also with one special-shaped (Type B) metal at the center of the beam, showed slightly higher rigidity than C-2. At the ultimate strength of $1.00M_y$, torsional deformation and local buckling occurred and the strength declined. Also, after the ultimate strength was reached, local deformation occurred with roofing members at their joints with the beam due to increased of deformation of the beam. C-4 provided with two special-shaped metals showed almost the same behavior as C-3. Its ultimate strength was $1.01M_y$ and the deterioration of strength after the ultimate strength was reached was less conspicuous, indicating that the Type B metals have appreciable buckling bracing effect. With both C-3 and C-4, torsional deformations showed axial symmetry against the bracing point.

4. Strength Test of Corner Knee Member of Main Frame

4.1 Outline of Test

The corner knee member of the main frame having a non-uniform section was subjected to a strength test. In a gable roof frame, a vertical load normally causes the point of maximum moment to occur at the corner knee member. In designing such a frame, safety is studied for each of the members, such as beams and columns, on the assumption that the out-of-plane deformation is completely held back at their joints. Actually, however, the out-of-plane deformation is not always held back completely at the corner knee member. Also, in actual design, the outer flanges of the beam and column members, as well as the corner knee members, are normally braced by a cross beam in the ridge direction, but the inner flanges are seldom provided with any lateral bracing members. However, bending stress due to vertical load, etc. becomes a compressive force applied to the inner flange and can cause out-of-plane buckling deformation of the vertex inside the corner knee member. This in turn can adversely affect the safety of the frame including type corner knee members. The new system frame, too, had to be studied from this viewpoint.
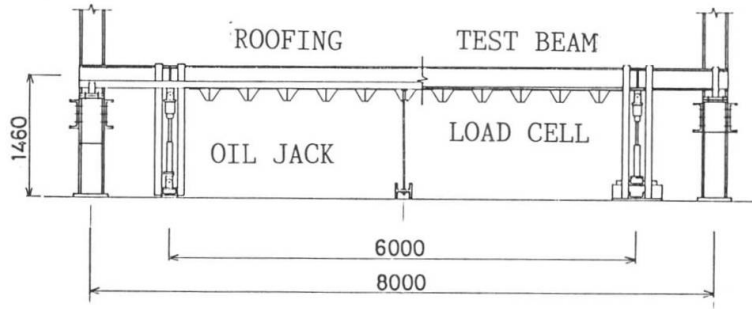
Fig.3 Test Set-up of Channel Steel

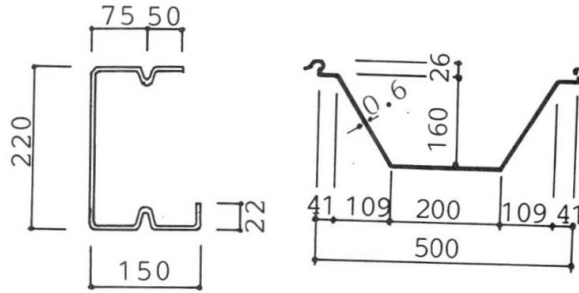| Test No.	Roofing	Metal	σ_y(t/cm^2)
C-1	no	no	2.76
C-2	yes	A	"
C-3	no	A,B$_1$	"
C-4	no	A,B$_2$	"
C-5	no	A,B$_1$	"

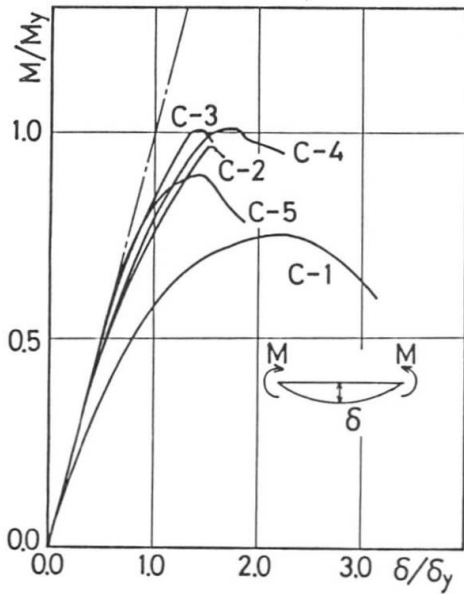

Table 1 Test Specimen of Channel Steel

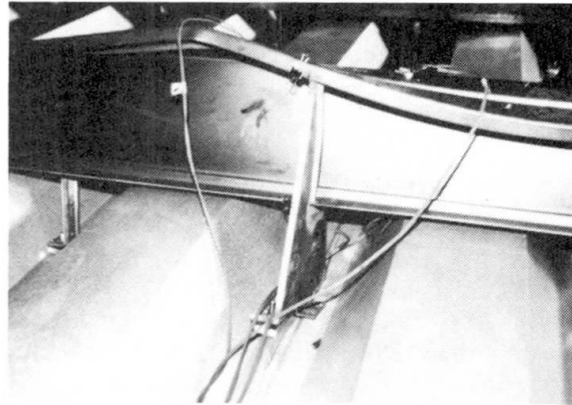Fig.4 Load-Deflection Curves of Channel Steel

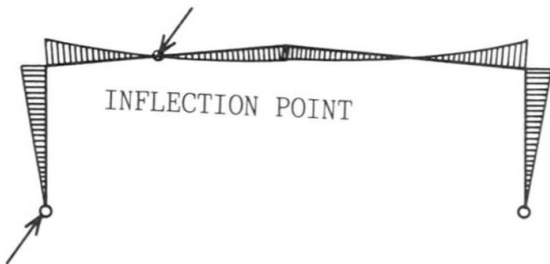Fig.5 Local Buckling of Channel Steel

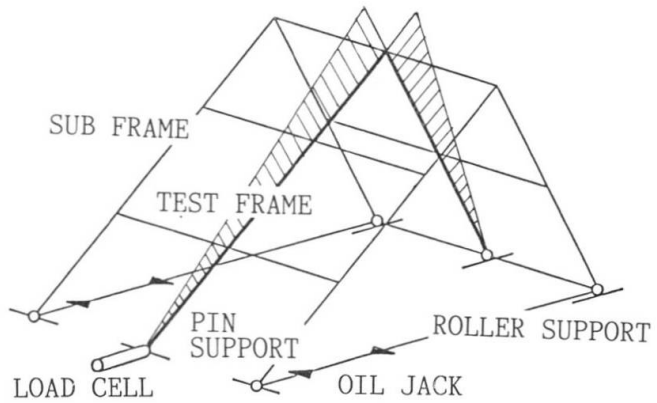Fig.6 Moment Distribution of Frame

Fig.7 Loading System of Frame

In the new system frame, the point of inflection of moment on the beam member a vertical load is located at approximately 6 m from the corner knee and the moment zero point on the column member is located in the column base from the design assumptions of the frame. Hence, the subassembly frame with the beam and column moment zero points as pins (see Fig.6,7) was subjected to the test. Test pieces used were 1/2 scale models of the actual frame.

For each test piece, two cross beams were connected to the column and one cross beam was connected to the beam. The parameters used for the testing were the type of bracing of the corner knee member and the presence or absence of stiffener bracing at the non-uniform section. A total of four different test pieces were used. The test pieces are outlined in Table 2.

4.2 Testing Equipment

The testing equipment used was such that it could measure the ultimate strength and deformation capacity of the corner knee member of the gable roof frame in as near the actual condition as possible. Compressive force was applied by pulling with a hydraulic jack the section between the column base as the pin support and the point on the beam corresponding to the point of inflection moment as the pin roller support. By so doing, a stress condition similar to the moment distribution under vertical load could be obtained (see Fig.7). At either and each test piece, a support frame was provided along the outer flange of the test piece to support the cross beam serving to brace the lateral buckling of the main frame. The support frames were placed on the same stand as the test piece was placed on so that they could be deformed in the same manner. Thus, the secondary members, such as the cross beam, are subject to the same in-plane deformation as the test piece. Load applied was detected by a load cell installed at the pin support of the test piece. As can be seen from the model diagram in Fig.7, this load cell detects only the force that is actually passed through the test piece. Fig.9 shows lateral buckling deformation of frame view of the testing.

4.3 Load-Deformation Relationship and Plastic Behavior

Fig.10 and 11 shows the load-deformation curves obtained as a result of the test. In the diagram, the one-dot chain line represents the result of a elastic analysis.

1) F-1

This test piece has no bracing plate at the starting point of the non-uniform section, and only the outer flange is braced at the vertex. The load-deformation relationship became nonlinear when a load of about 1.75 tons was applied. As external force was increased, the amount of deformation increased. The ultimate strength was 2.75 tons, and thereafter, the strength decressed sharply. At a load of about 2.7 tons, local buckling deformation occurred at around the starting point of the non-uniform section of the beam. As the load was increased further, the local buckling deformation and out-of-plane deformation at the point continued to increase.

2) F-2

This test piece is the same as F-1, except that both the outer and inner flanges are braced at the vertex of the corner knee member. It showed almost the same load-deformation relationship as F-1. The ultimate strength was 2.8 tons. No marked difference in ultimate strength could be observed among F-2 with both flanges braced, and F-1 with only the tension flange braced. This is due to the fact that the local buckling precedes another buckling and that the bracing member at the vertex appreciably held back the out-of-plane deformation of the compression flange owing to stiffner. Incidentally, the vertex bracing member attached to the tension flange of F-1 was subjected to greater bending stress than that of F-2.

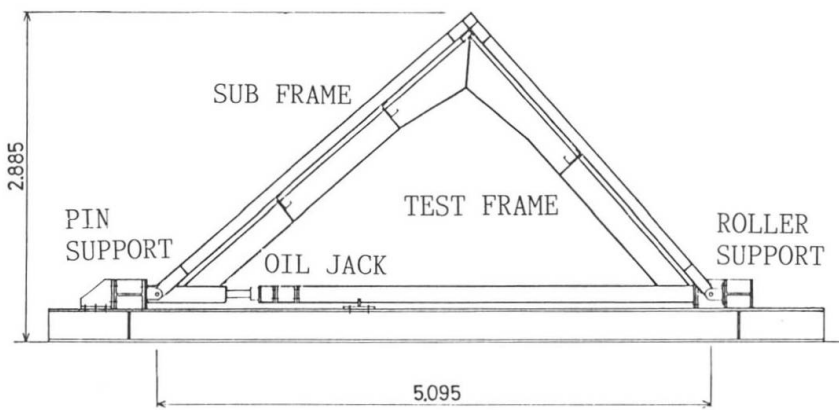| Test No.	Section	$\sigma_y(t/cm^2)$	Stiffened Plate	Lateral Bracing at Corner Knee
F-1	BH-200×100×3.6×6	3.3	no	Tens. Flange
F-2	BH-300×100×3.6×6		no	Both Flanges
F-3			yes	Tens. Flange
F-4			yes	Both Flanges

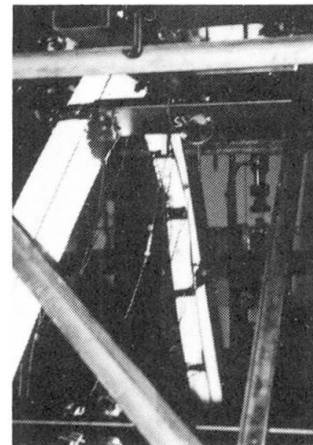Table 2 Dimensions of Frame Test

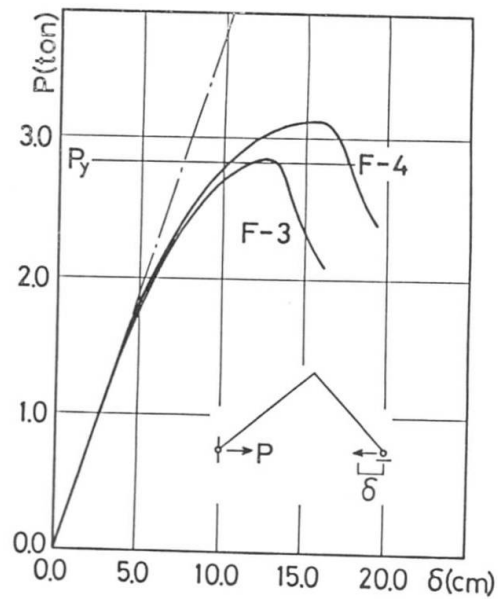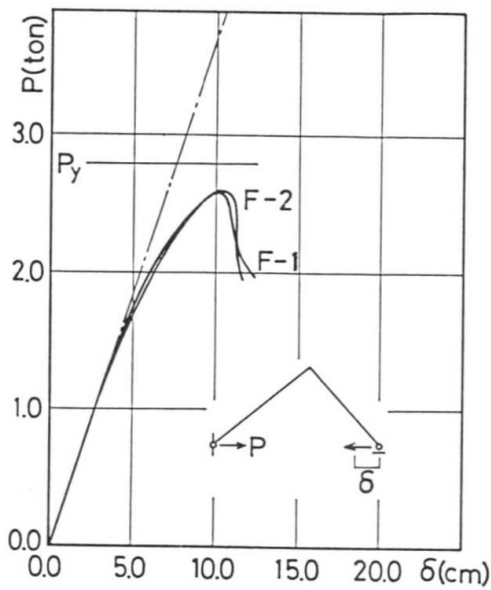Fig.8 Test Set-up of Frame

Fig.9 Lateral Buckling of Frame

Fig.10 Load-Deflection Curves of Frame

Fig.11 Load-Deflection Curves of Frame

3) F-3

This test piece is provided with a local buckling bracing plate at the starting point of the non-uniform section. Only the tension flange of the corner knee was braced. The load-deformation curve in the elastic region of F-3 was exactly the same as those of F-1 and F-2. The load-deformation relationship became nonlinear when a load of about 2.0 tons was applied. After the ultimate strength of 2.8 tons was reached, F-3 showed deterioration in strength. The lateral buckling deformation after the ultimate strength was reached was inversely symmetrical with that on the opposite side of the cross beam, indicating that the cross beam of unequal leg channel steel served as an effective buckling bracing member. With this test piece, the compression flange at the vartex of the corner knee had not been braced, hence a small amount of out-of-plane deformation occurred, making the inversely symmetrical deformation somewhat incomplete.

4) F-4

This test piece is the same as F-3, except that both the tension and compression flanges were braced at the vertex of the corner knee member. The rigidity deteriorated slightly when a load of about 2.0 tons was applied. However, the ultimate strength reached 3.25 tons. The type of breaking was out-of-plane lateral buckling of the compression flange. The buckling deformation was sufficiently held back by the cross beam and vertex bracing member, and F-4 showed a perfect S-shaped deformation. Compared with the other three test pieces, this test piece showed greater deformation capacity and a plasticity coefficient (μ) of about 1.5.

5. Study of Frame Design

Based on the above-mentioned test results, the new system frame was reviewed. In designing main frame member of non-uniform section, it was anticipated that the starting point of the non-uniform section and the corner knee member would yield at the same time. In the test, however, plasticization of the starting point of the non-uniform section progressed earlier, and hence the ultimate strength was determined by the lateral buckling deformation of the compression flange containing that point. This indicates that in order to obtain a more efficient non-uniform section, it will be necessary to let the starting point of the non-uniform section of the column member come closer to the column base. As for the bracing of the corner knee member, since the main frame is a full web provided with a stiffener, only the tension flange need be braced from the viewpoint of strength, provided that the cross beam has sufficient rigidity. However, in order to ensure good deformation behavior in the plastic region and to maintain sufficient safety of the frame, it would be better to brace the compression flange, as well as the tension flange. The effect of combining the cold formed channel steel used as the cross beam with the roofing member can be secured by use of special-shaped metals. With a 6 m span beam, it would be sufficient to provide one special metal at the center. The use of this cross beam in the new system frame has made it possible to eliminate stud members and sub-beams from the design.

6. Conclusion

This paper has outlined the newly developed system frame, confirmed the validity of the frame design by tests, and presented problems involved.

The test results have proved that the new system frame as a whole is valid. Compared with conventional system frames, the present system has made it possible to reduce the frame weight by 15 to 20% and to shorten significantly the time required for building the frame.