UDC 691 . 714 : 691 . 11

Engineering Development of a New Structuring System for Wooden Two-by-four Housing Based on the New Optimized Designing Concept

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Abstract

Mitsui Homes Co. and Nippon Steel Corporation have developed a new structuring system for wooden two-by-four housing to secure cost competitiveness and improve productivity. This is meant to bring "steel culture" into "wood culture" of two-by-four housing to pursue what is called "hybridization", the optimum values of design, production, logistics, distribution and construction from each culture. The housing industry has ended the era of continual growth and entered the severe competitive age. The direction of this hybridization is expected to be a basic standard to overcome such competitive age.

1. Introduction

Wooden two-by-four housing of framework wall engineering was introduced from North America in the late 1960s. After that, the number of such housing has been steadily increasing mainly in urban areas, and especially during the five years from 1991, the growth reached the scale of 100,000 housing starts annually, 10% of the detached house market.

Wooden two-by-four housing is characterized, as its name shows, by basically 2 inch×4 inch wood being tightly connected to surface material such as structural plywood to make walls, and tight connection to floor after the arrangement based on the layout form a wall-style structure with high antiseismic safety. Attention has been given to the high performance as an energy efficient house with the wall-style structure easily securing heat insulation and air-tightness. But on the other hand, this type of house has been recently facing two big environmental changes which must be solved in order to secure cost competitiveness regarding housing production.

One change is that the need for larger space like a bigger salon for a living room has been increasing. Take the floor for example. A larger space expands the intervals of wall which supports the floor, and the floor joist section grows bigger. For this reason, the way to secure ceiling height could be to heighten the whole building, which substantially boosts the construction costs. Actually, longer floor joists because of the need for bigger space is partially arranged to secure the building and ceiling height as it is. But creating drastic new techniques to deal with bigger space has become an urgent issue.

The other change is that much wood is imported. The lumber prices are greatly affected by fluctuating exchange rates or suppliers' businesses and have trended upward on a long-term basis. In addition, wood with bigger section and better quality, whose application is expected to increase as a result of larger space needs, becomes comparatively expensive.

In order for wooden two-by-four housing to further spread in the future, it is important to secure cost competitiveness by creating techniques that can deal with changes in environment surrounding this housing production. The performance evaluation standard for steel house structures approved the use of zinc coated steel of more than 0.8 mm and less than 2.3 mm thickness in July 1995. Mitsui Homes Co. and Nippon Steel Corporation have jointly developed a new structuring system by hybridizing the respective advantages of wood and

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steel.

This paper reports on the fundamental concept of hybridization, targeted parts selection for development and concrete development.

2. Fundamental Concept of Hybridization and Targeted Parts for Development

2.1 Fundamental concept of hybridization

The purpose of hybridization lies in arranging by optimizing different materials of wood and steel and in exactly ensuring problem solution. Wood has superior heat insulation and bondability or workability at the building site, but has unstable price or quality and is low in strength and rigidity. On the other hand, steel is high in strength or rigidity and stable in price or quality, but is problematic in heat insulation and bondability or workability at the building site.

Based on the complementary relationship between wood and steel, some parts of the current wooden two-by-four housing are replaced by steel to utilize its advantageous characteristics. Housing with the following combined advantages will be realized:

(1) superior in heat insulation and air-tightness (wood),
(2) easy bonding and working at the building site (wood),
(3) easy to deal with larger spaces by using high-strength and high-rigidity (steel), and
(4) stable in price and quality (steel).

It will be possible to precisely deal with changes in environment surrounding housing production.

2.2 Selection of targeted parts for development

In selecting targeted parts for development, three parts were chosen where a conventional wooden structure is highly likely to have increased costs and problem solving is urgent.

2.2.1 Hut truss

Hut truss is a major part constituting comparatively large space and the component materials require high strength and high rigidity. Wooden hut truss requires large cross-section and much volume. The possibility is that using steel with high strength and rigidity will deal with the requirement for further larger space by securing cost competitiveness.

2.2.2 Second floor arrangement

For floor joists, the longest length and biggest cross-section of wood is being utilized among component materials for wooden two-by-four housing.

The requirement of living space whose span exceeds 4,550 mm is dealt with by bigger section of floor joist and using a greater number of them at present. From the viewpoint of curtailing cost increases, drastic solution by using steel is expected.

2.2.3 First ceiling joist

Ceiling joist is a member used for the basis of ceiling finish. Because the precision of finish depends directly on member precision of the joists, expensive but rigid laminated timbers have been used intentionally after the warping and bending are corrected. Further higher costs are expected in the future with even bigger spaces. Thus, it is a pressing need for the steel-wood hybrid joist to realize cost reduction while keeping the finish precision (See **Fig. 1**).

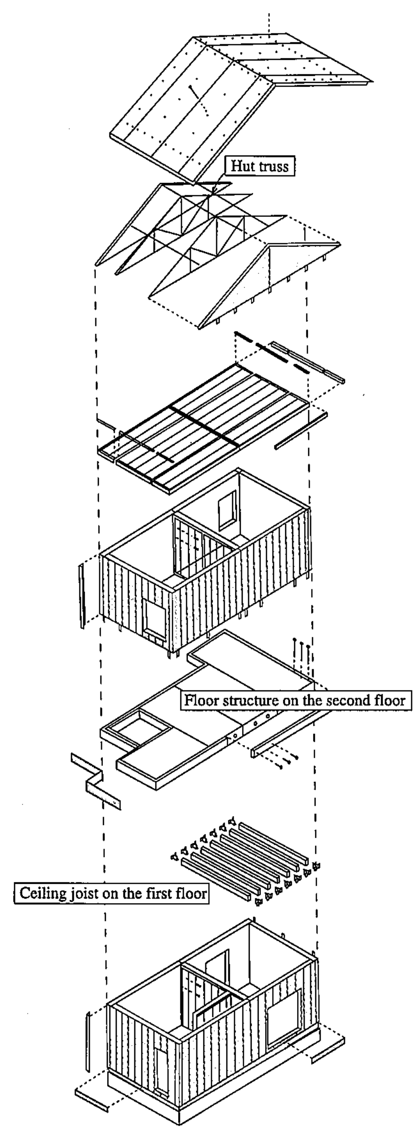


Fig. 1 Targeted parts for development

3. Individual Part Development Targeted for Hybridization

3.1 Hut truss

3.1.1 Problems for development

Because of the structural characteristics of the truss, stress is concentrated at the joints. Meticulous consideration is required in its design. Especially, stress-concentrated steel sheet can easily deform locally. So for the development of steel sheet trusses, it is necessary to diffuse concentrated stress and develop joints which suppress the occurrence of local deformation.

3.1.2 Development toward problem-solving

In order to grasp quantitatively the effect of local deformation at the truss joints on the overall strength, a steel truss with 7,280-mm span was tested under loading. The test truss was loaded repeatedly or loaded until destruction by a hydraulic jack at the two points near the center of the upper chord member. To reproduce the actual hut structure correctly, jigs were installed horizontally at 910-mm intervals so that the deformation of the upper chord member in the direction outside the face was restrained (See **Photo 1**).

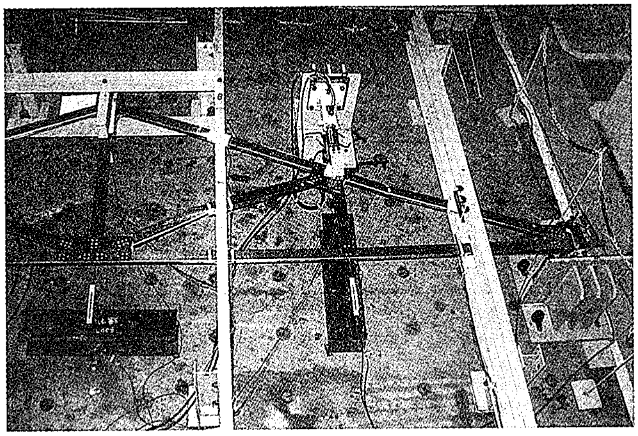


Photo 1 Scene of the structural test of hut truss

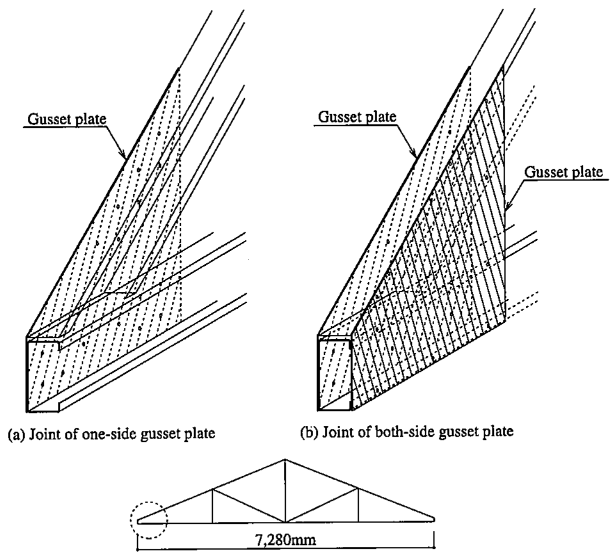


Fig. 2 Joints of one-side and both-side gusset plates

Fig. 2(a) shows the case of joining the truss chord member with a gusset plate at one side only. Local deformation occurred on the gusset plate from the first stage of the repeated loading by the effect of the eccentricity between the load-applied face and the gusset plate face. The maximum load was 2,448 kgf, only 2.35 times the design load of 1,040 kgf. To prevent local deformation at joints due to the eccentricity, the truss chord member was joined with gusset plates on both sides (See Fig. 2(b)) and again tested.

The result was that the maximum load became 3,556 kgf, endurance improvement was confirmed at 3.34 times the design load and about 1.4 times the one-side joint figure. Displacement at the design load was 5.58 mm, equivalent to 1/1,305 of the 7,280-mm span. As shown in **Fig. 3**, since analysis could reproduce a high correlation between load and displacement in the test, it was shown that a truss using steel sheet can be designed following the conventional structural calculation guideline by preventing as much as possible local deformation at joints.

3.1.3 Construction verification by actual buildings

Since design technique was established, design optimization such as reduction in the number of parts constituting the entire hut structure including truss, was conducted by utilizing the characteristics of steel strength. The optimized hut structure was verified with the actual single-family house construction (See **Photo 2**). By increasing the ratio of factory processing, an advantage of steel, and decreasing the amount of site joining, a disadvantage of steel, workability including construction precision of the hybrid structure exceeded that of the conventional wooden hut structure.

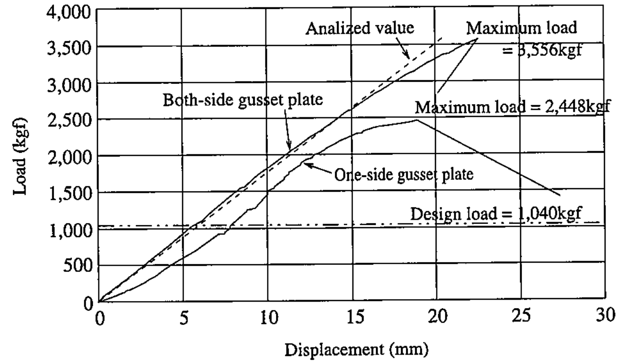


Fig. 3 Load-displacement curve of hut truss

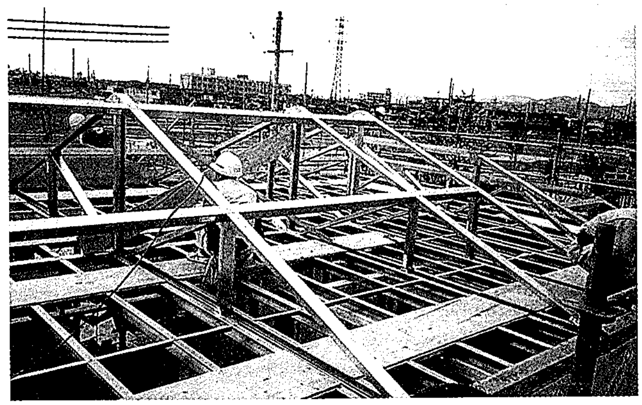


Photo 2 Operation test of hut structure for a detached house

3.2 Floor structure on the second floor

3.2.1 Problems for development

Among the many performance elements required for the second floor structure, development was conducted on structural and vibrational performances as a first step.

There are two roles for the structural performance of the second floor structure. One role is a transmission of the vertical force applied on the second floor by the dead load and live load to the first-floor walls, and the other is a transmission of the horizontal force applied on the second-floor wall by storm or earthquake to the first-floor walls. In using steel for the floor, there are no problems with the vertical force, provided that some measures are taken to prevent local deformation of the floor joist ends at the joints with walls, like hut trusses. On the other hand, for transmitting the horizontal force, the conventional construction method has an all-wooden transmission path for horizontal force. In the case of a steel structure, horizontal force is transmitted from the wooden second-floor walls to the wooden second-floor floor plywood, then transmitted to the wooden first floor walls through steel floor joists, as shown in **Fig. 4**. Horizontal force transmits just through wood-steel hybridization, thus requiring a quantitative grasp of the series of horizontal force transmission abilities.

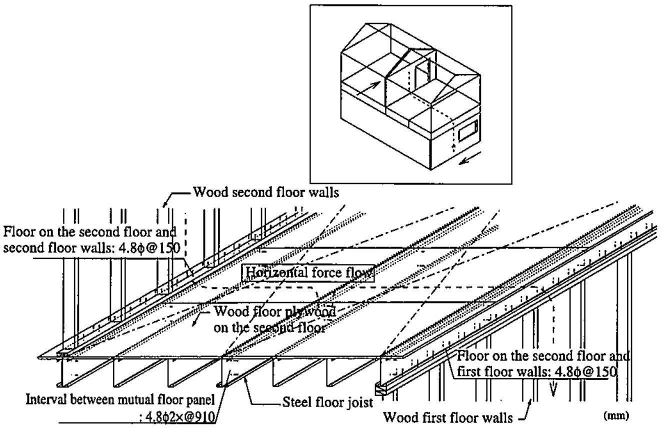


Fig. 4 Horizontal force conveying path of hybrid floor structure

The role of the floor structure on the second floor regarding oscillation ability is to prevent oscillation because it is disagreeable to humans and to eliminate quickly any oscillation occurring on the floor. Steel has high strength and rigidity but is inferior to wood in quickly eliminating oscillation, or what is called oscillation damping ability. Based on this, it is necessary to develop an oscillation-prevention mechanism which minimize cost increases.

3.2.2 Development of structural problem-solving

Regarding the joint transmission path of horizontal force, using 4.8-mm diameter screws, the frame material of second floor walls and structural plywood on second floor were joined at 150-mm intervals, floor panel frame materials were joined mutually at the intervals of 910-mm, and second floor walls and first floor walls were joined at intervals of 150-mm. The test body was made with a specification similar to the specification for conventional wooden structure (See **Photo 3**). The size of the test body was set at 10,920 mm× 3,640 mm, with 3 steel floor panels of 1,820 mm×3,640 mm arranged. The design load of 4,200 kgf was loaded repeatedly, parallel to the floor joist.

The result is shown in **Fig. 5**. The maximum load is 10,920 kgf, 2.6 times the design load and horizontal deflection at the design load is 21.2 mm (1/515 of span). Furthermore, it was confirmed that the test body shows elastic deformation properties until loading the design load and slide and opening between floor panels at the design load is each 0.1 mm, less than 0.5 mm. This means that the transmission path of horizontal force in the hybridized structure is nearly equivalent to that in the conventional wooden structure, provided that the joining intervals are almost the same.

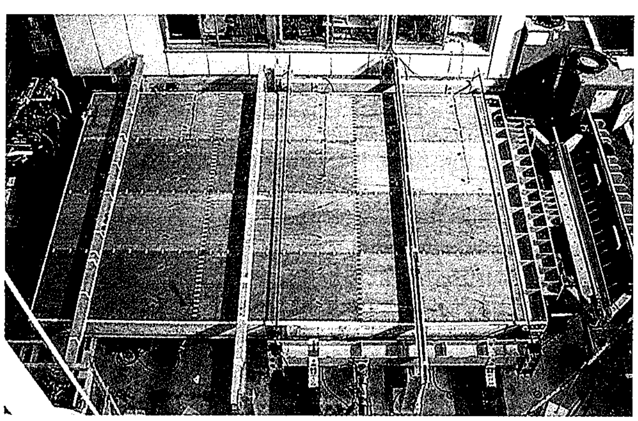


Photo 3 Test scene regarding quantitative grasp of horizontal conveying ability

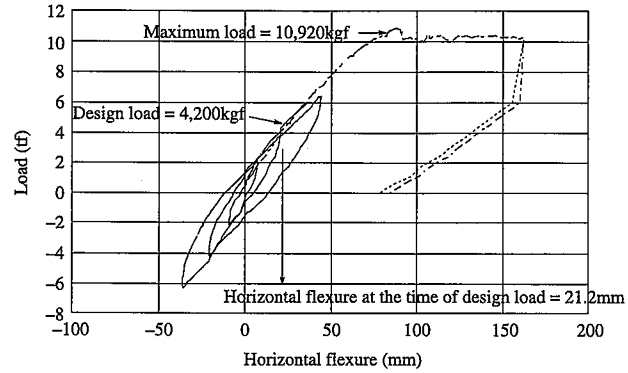


Fig. 5 Load-deformation curve of test object

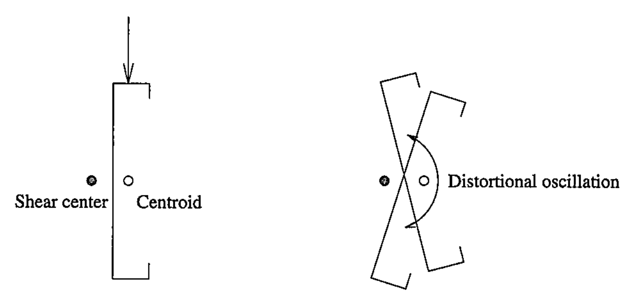
3.2.3 Development a solution to oscillation

Large lip channel using zinc plated steel for the floor structure can be procured at costs similar to that of distributed steel because a production system has already been arranged as a member for steel houses. In selecting floor members, the application of lip channel is reasonable in terms of cost. But there have been some fears regarding the lip channel structures hitherto, since they will encounter oscillatory distortion by vertical impact load due to the discrepancy between shear center and centroid (See **Fig. 6**).

In order to clarify the oscillation properties of lip channel, a mass of 3 kg-clay was dropped from a height of 50 mm at a site where steel floor panel was actually installed. Wave-forms of vertical and horizontal acceleration were measured for the lip channel used as floor joist.

The result is shown in **Fig. 7**. It was shown that horizontal oscillation at the lower end joist is more than twice the vertical oscillation and that the vertical dominant frequency is 39.1 Hz while the horizontal one is 19.5 Hz, approaching the range that humans can easily feel. It was also proved that the oscillation damping constant for horizontal direction is 1.7%, a very low damping ability, while that for vertical direction is 12.1%, quickly reducing the oscillation.

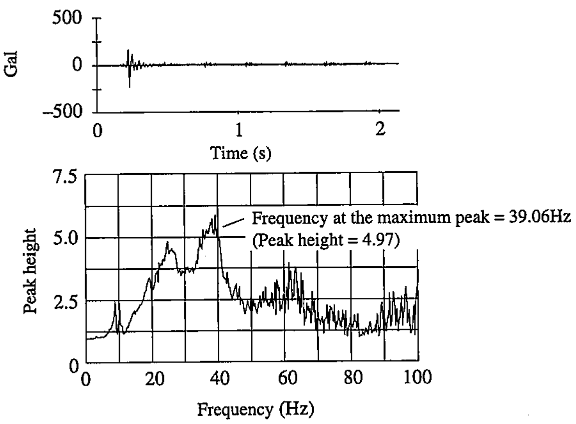
As improvement measures, **Fig. 8** shows that simple hardware was installed at the center of the floor joist to restrain horizontal oscillation of the lower flange of lip channel. In addition, so as to improve the damping of horizontal oscillation, such device was added as hardware makes a chord oscillation in the direction of Fig. 8(b), when oscillation from the lower flange of the channel is transmitted to the simple hardware.



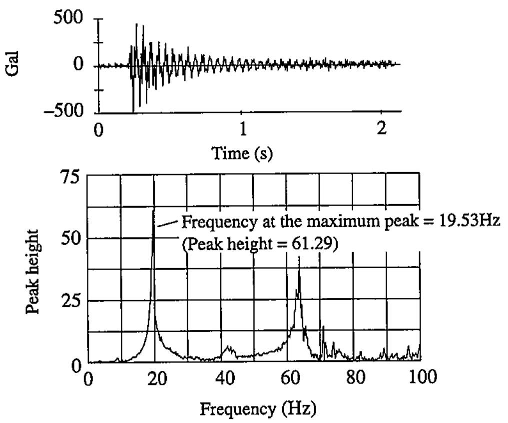
(a) Discrepancy between shear center and centroid

(b) Distortional oscillation

Fig. 6 Structural properties of lip channel

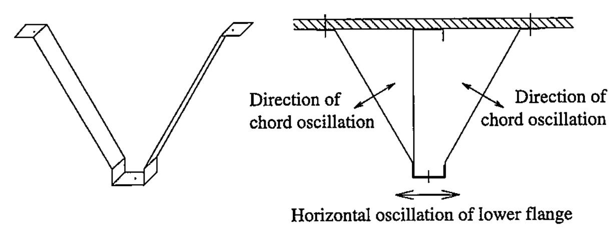


(a) Wave form and Fourier spectrum of vertical acceleration



(b) Horizontal acceleration waves and Fourier spectrum

Fig. 7 Oscillation properties of lip channel (before improvement)



(a) Bird's-eye view of hardware (b) Fitting of hardware to channel

Fig. 8 Oscillation restraint hardware

The result of oscillation measurement after the improvement saw no change in vertical acceleration and dominant frequency from that before the improvement, but horizontally, as in **Fig. 9**, only one installation of oscillation restraint hardware at the center of the 4,550 mm span lessened acceleration by about 30% and the dominant frequency changed from 19.5 Hz to 50.3 Hz, far from the range that humans feel disagreeable. The damping constant changed from 1.7% before the measures to 10.6%, and vibrational performance was increased to a level with no practical problems.

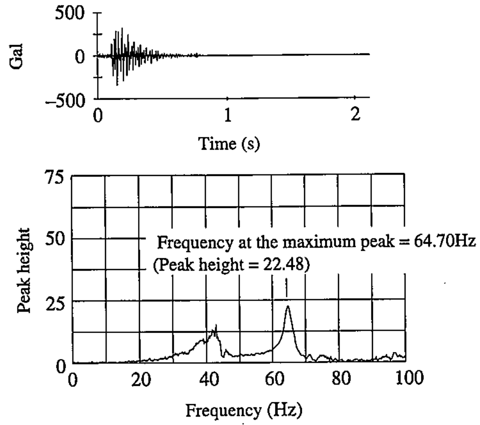


Fig. 9 Oscillation properties of lip channel (after improvement)

3.3 First floor ceiling joist

3.3.1 Development problems

One of the reasons why the number of wooden two-by-four housing starts has been recently increasing lies in the great freedom of layout, like free plan. This arises from the characteristics of wood giving superior workability and bondability. In the case of replacing wood members with steel ones for conventional first ceiling joists, the problem is how to secure site workability and bondability, making use of steel's characteristics, that allows highly precise factory processing, unlike wood (See **Fig. 10**).

3.3.2 Development toward problem-solving

In problem-solving, the first thinking to note is the difference in section shapes between wood and steel. Section is hollow when making steel member section box shapes. A method was devised whereby the length of joist is freely adjusted without site processing by sliding a fitting hardware nested in the hollow space.

With this method alone, however, the fitting hardware can easily slide within the box joist. To prevent the sliding, the hardware was manufactured delicately and precisely at a factory. Concretely, a slight angle was placed on the hardware. Thus, if the hardwares at the both ends are fastened to neighboring wood members, the hardware does not slide by a slight external force, even though it was not fastened to the box joist.

3.3.3 Engineering verification by actual operation

The steel ceiling joist system developed has a relatively small load on building production facilities for actual machines, and the

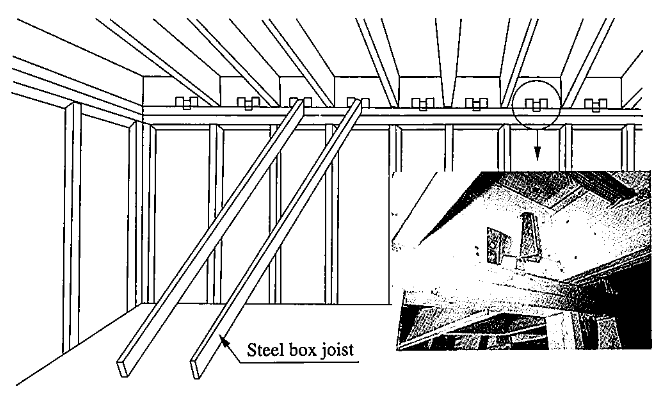


Fig. 10 Developed steel ceiling joist system

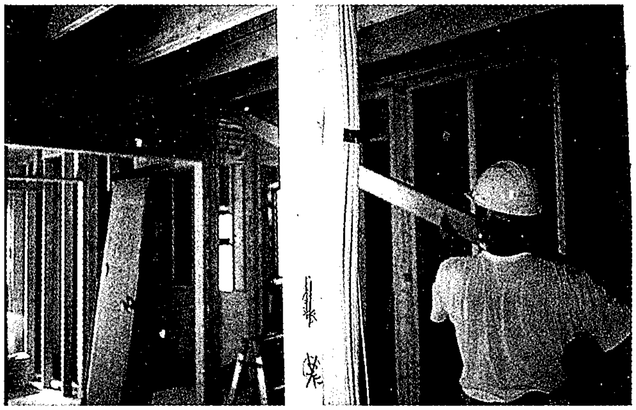


Photo 4 Operation scene of steel hanging system

expected effect of reducing building costs was great, so operation verification in actual buildings and parts improvement have been energetically implemented. As a result of trial use in 16 actual buildings, ceiling joists could be lightened to 1.3 kg per 1 m, a 25% reduction compared with conventional joists. And by omitting the ceiling joist joint and attached hardware, the joint number per ceiling joist could be decreased from 12 points to 8, a 33% reduction. Consequently, one-man installation rather than the conventional two-man job became possible, thus achieving significant productivity improvement (See **Photo 4**).

4. Conclusion

For the past two years, our development has been based on the fundamental idea that a new housing construction method should be realized which secures cost competitiveness by integrating "steel culture" into the "wood culture" of wooden two-by-four housing.

As a result, although some problems still remain, such as securing fire-prevention ability for the floor structure on the second floor, there are a series of prospects for design, production, distribution, logistics, and operation for ceiling joist on the first floor. Thus, hybrid specifications are being incorporated into product menus.

It is said that the housing industry has currently ended the era of continuous growth and entered a severely competitive age. When considering the situation where a decrease in the number of construction workers such as carpenters for housing is unavoidable in the future, and where housing construction largely depends on human labor, though more prefabrication and mechanization at operation sites are advancing, we expect more than ever serious development of a new housing construction method aiming at cost competitiveness and productivity improvement. The direction of this hybridization, while making use of the mutual advantages of wood and steel, can be called just a basic standard with respect to these movements.

5. Acknowledgements

The authors would like to thank those involved in this development, Mr. Makoto Kawai, Mr. Ichiro Fukuda and Mr. Osamu Ohashi of Mitsui Home Technical Development Institute as well as Mr. Jyunichi Kosaka and Yasuo Takeshima of Panel Production Section of Manufacturing Control Department, and again express their thanks for the stable and persistent work by those concerned, with their high challenging spirit and motivation to achieve the goal.