NIPPON STEEL TECHNICAL REPORT No. 79 JANUARY 1999

UDC 691 . 714 : 669 . 586 . 5 : 669 . 14 - 415 : 69 . 024 . 8

Engineering Development of Superior Framing System for Roof of the Residential and Commercial Housing Using Zinc Thin Plate Materials

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Abstract

Amid worsening problems of aging construction workers and shortage of human resources, Asahi Chemical Industry Co. Ltd., Nippon Steel Corporation and Sanko Metal Industrial Co. Ltd. have jointly developed a superior framing system which realizes lowering costs and increasing productivity of residential and commercial housing construction using zinc thin plate materials. This is the completely pre-engineered and computerized components system for roof framing, using zinc thin plate materials with over 0.8mm and under 2.3mm in thickness whose use was approved based on the performance evaluation standard for steel framed housing in July 1995. Construction workers can just set up roof framing by following manuals on site to assemble such pre-engineered components. Lowering cost and improving productivity are expected to become inevitable subjects for housing industry to overcome. This innovative system can indicate appropriate archetype as the direction for future of housing development.

1. Introduction

Triggered partly by the increase in consumption tax rate, the housing market has rapidly cooled down. The number of housing construction starts in 1997 was 1.34 million, 17.7% lower than the previous year, which has been above the 1.3 million mark since 1991. Amid the serious housing depression, there is more discussion of reducing costs and improving productivity of housing. Our country's structural problems, aging carpenters and labor shortage can not be avoided in this discussion.

According to the census, there were 850,000 carpenters in 1970 and the number increased temporarily to 940,000 in 1980. But after that, the number decreased to 730,000 in 1990 and some expect the number to be less than 500,000 in 2000. As for the age structure, in 1970, those who were under 40 constituted less than 70% of the total and those over 40 constituted more than 30%, which was a pyramid structure. Twenty years later, in 1990, those under 40 constituted more than 30% and those over 40 were less than 70%. This is the reverse pyramid indicating the number of carpenters will decrease in the future (**Fig 1**). It is becoming urgently important to develop a housing system from a new perspective, dealing with the aging and shortage of construction workers like carpenters.

Nippon Steel Corporation has been working to develop a new housing system which uses zinc thin plates over 0.8 mm and under 2.3 mm in thickness in order to realize housing cost reduction and to

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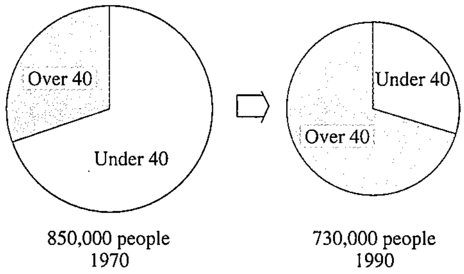

Fig. 1 Reality of aging carpenters and labor shortage

improve productivity. This is based on the opportunity of approval in Article 38 of Building Standards Law, based on the performance evaluation standards for steel framed housing, which started in July, 1995.

Compared with wood, zinc-coated thin plates:

(1) have high strength and rigidity,

(2) can realize high process precision with factory processing,

(3) assure that anti-rust specifications to suit varying purposes can be added, and

(4) make possible highly productive roll forming.

These are the four major superior characteristics.

This report introduces the fundamental ideas and outlines: the development of a superior roof framing which can realize cost reduction and improving productivity, taking the example of the roof framing system of Asahi Chemical Industry Co. Ltd. (abbreviated Asahi Chemical hereinafter) which has worked from a completely new perspective, while drawing out the characteristics of these superior zinc thin plates, and the building of a production system at Sanko Metal Industrial Co. Ltd. (abbreviated Sanko Metal hereinafter).

2. Development of Roof Framing System Using Zinc Thin Plates

2.1 Development background

Targeted development is a roof framing system, which is a roof foundation for detached houses or housing complex. The regular method at Asahi Chemical was such a system as constructing a wooden roof framing using mainly two-by-four wood (section 38 mm × 89 mm, abbreviated 2 × 4 hereinafter) onto the structure surrounded by light concrete board in the outer periphery and a top surface of steel framework which is made up of pillars, beams and braces.

This system is to form the roof framing by continuously installing beams, called rafters between the main house panels which install the eave beams and the ceiling parts of the above steel frameworks (**Fig. 2**). Since wood is used for the roof truss framing, some problems existed:

(1) It is must be constructed by professional carpenters.

(2) Quality varies, depending on the skills of carpenters.

(3) Joint points between wood are many, and tie-ins are complicated, which restrains limit efforts to shorten the work period since processing at each site is necessary.

(4) In response to the recent situation where quality wood is difficult to obtain, there is worry about the endurance of the superior framing system itself.

2.2 Proposal of a new roof framing system

Based on the problems of the current roof framing system, what matters in considering a new system is to draw out the characteristics of zinc thin plates to realize what conventional wood couldn't do. "Making kits of roof framing parts" was founded on such an idea and was devised. These kit parts are produced at factories in advance and carried into construction sites where workers can easily make roof framing of complex roof shapes only by assembling parts according to the manual.

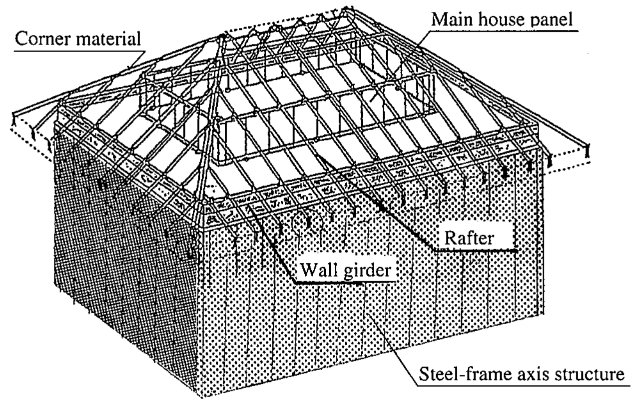

Fig. 2 Outline of roof framing system of Asahi Chemical

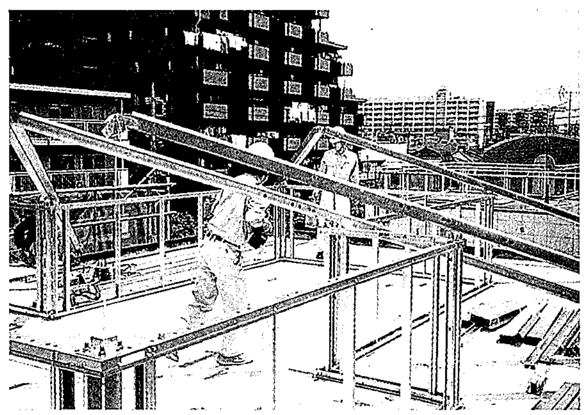

Photo 1 Assembling site of roof framing kit parts

That is, by making kits of roof framing parts,

(1) The roof framing system can be used by workers without special skills.

(2) Stable quality factory-made parts are used.

(3) The work period is shortened so that assembling can be concentrated by eliminating the parts processing at the site.

(4) Endurance is improved by using zinc thin plates.

Thus, the above effects can be expected (**Photo 1**).

2.3 Development of roof truss framing kit parts

Much 2 × 4 wood materials are used in the conventional roof framing using wood. The first issue in developing roof framing kit parts was how these 2 × 4 wood materials might be replaced with handy steel products. The second issue was how to develop productive joint methods for actually installing developed steel products.

The following are technical developments answering these two developmental issues.

2.3.1 Development of steel products replacing 2 × 4 wood materials

2.3.1.1 Optimizing sections of steel products

In the present roof framing using wood, where 2 × 4 wood materials (**Fig. 3**(a)) are most frequently used there are parts called rafters. These rafters with oblong sections have the role of bearing not only roof weight but also wind or snow load and transferring load to the structure of the steel framework.

In the case of replacing steel for wood with oblong sections, the general methods are to form zinc-coated thin plates into box sections with the same outer shapes as wood (Fig. 3(b)) or simple C-shape sections (Fig. 3(c)). But when the box sections are fastened to other members, it is necessary to join by through bolts through attaching steel plates called gusset plates from both sides, which makes the joint itself complicated. And as for the C-shape sections, the joint itself is simplified because there is one gusset plate. Still, the section shapes are asymmetrical on both sides, so the faces the load acts on and the gusset plate, the attached face, have an eccentricity relationship. In general, this eccentricity causes a lowering of member strength.

Fig. 3(d) is a section designed for the purpose of ensuring simplified joints as well as agreeing in position between the faces the load acts on and the attached faces. In order to improve the structural strength of this section, stiffeners by lips (Fig. 3(e)) are formed at the first and last sectional ends, and to ultimately minimize cracking of the zinc-layer in roll forming, enlarged bend radius on the sectional bend areas (Fig. 3(f)) is ensured, by which the sectional shapes are optimized stepwise.

2.3.1.2 Establishment of design techniques concerning optimum sections

Rafters used for the roof framing support roof weight and wind or snow load, but flanges of member sections get compressed and buckle when they receiving load greater than the allowable endurance. Although the system guidelines for light steel structural design standardized by Japan Construction Society have established design techniques for such general thin plate sections as C-type sections, they can not be applied to arbitrary sections based on users' needs which were optimized in this development. Furthermore, plywood panels for structural use are in fact screwed to the upper areas of steel members. It is said that structural strength of members are generally improved when combined with this structural plywood, but design techniques which can grasp this quantitatively are totally undeveloped.

To expand the application of zinc thin plates in the housing construction field in the future, technical clarification has been started in order to establish challenging technical areas which have not been started yet by Japan Construction Society.

Regarding member buckling, there are big differences between buckling phenomena with and without plywood. Without plywood, as shown in **Fig. 4**, the shapes of member sections are maintained, until they at last begin to buckle. On the other hand, as in **Fig. 5** it turns out that when members are bound by plywood, only the weak binding areas buckle such as partially falling sideways.

The methods for evaluating buckling strength shown in system guidelines for light steel structural design by Japan Construction Society do not consider that the binding effects of member sections by plywood and member endurance was evaluated significantly lower than its actual value. That means quantitative grasping binding effects of member sections by plywood is the technical issue for establishing design techniques.

In order to quantitatively grasp the binding effects of plywood member sections and establish their use in design techniques, first of all, a testing structure is manufactured to serve as a model (**Fig. 6**) when up-draft load acts on rafters during storms. For actual manufacturing, two rafters at eaves are taken out as **Fig. 7** shows, in order to reproduce the same stress as bending moment acting on rafters

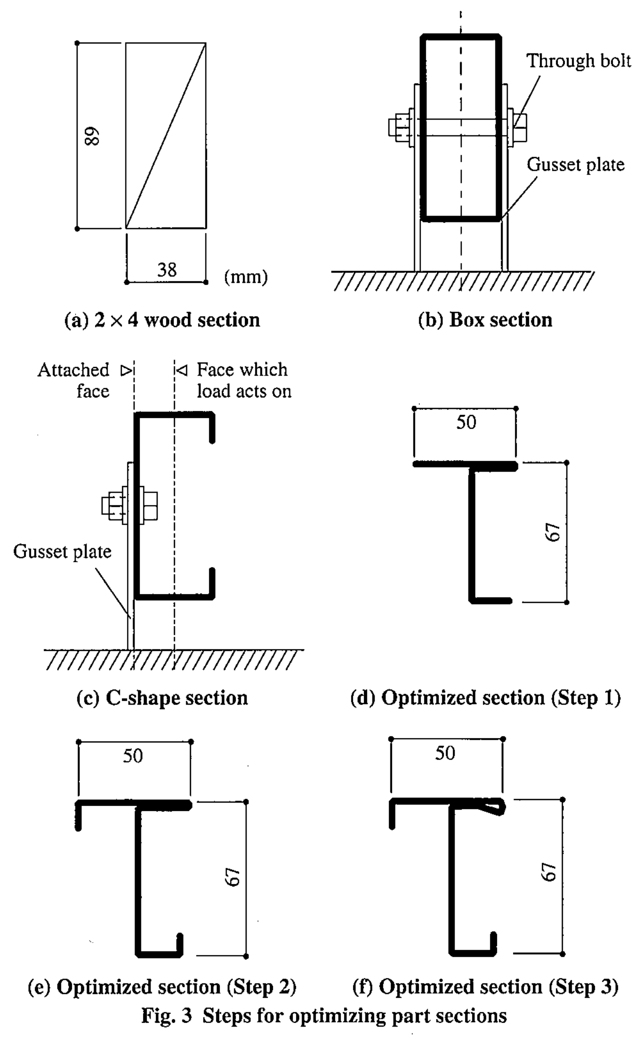

Fig. 3 Steps for optimizing part sections

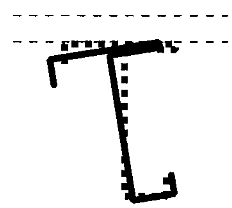

Fig. 4 Buckling in member section without plywood binding

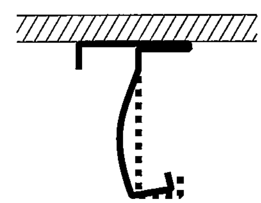

Fig. 5 Buckling in member section with plywood binding

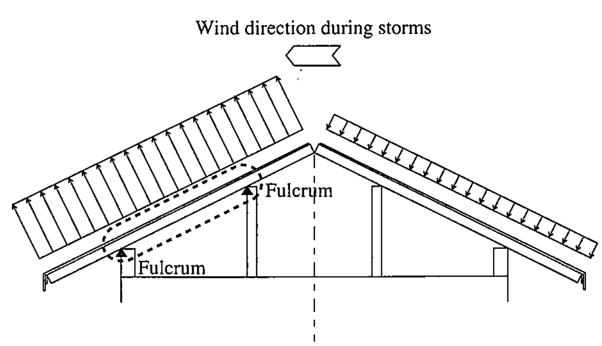

Fig. 6 Load image putting on rafter during storms

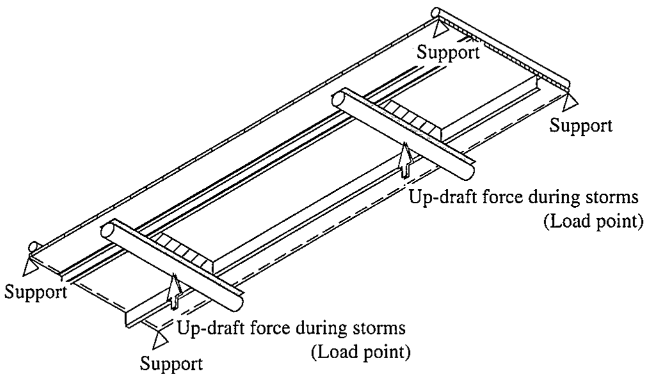

Fig. 7 Picture of testing structure reproducing eaves

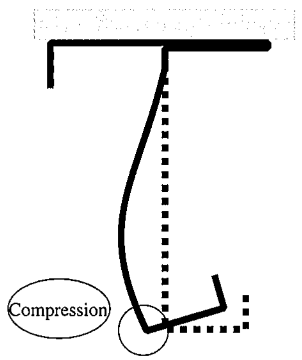

Fig. 8 Distortional buckling at lower flange

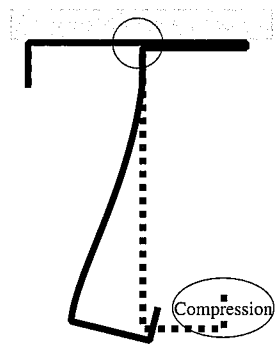

Fig. 9 Distortional buckling of web

during a storm. The support span of the present testing structure is 2,400 mm, the distance between the central loading points 1,220 mm and the two rafters are fixed so that the pitch is less than 300 mm between structural plywood with 12.5 mm thickness and self-tapping screws.

Next, while applying load on the testing structure from loading points, the deformation of member sections themselves and the whole deformation as testing structure are carefully observed. As a result, it was found that the flange and web each falls sideways with the round marks shown in **Figs. 8 and 9** as fulcrums, since the upper flange at member sections is bound by plywood. This buckling deforms as part of the sections falls sideways with the loading and is intermediate between the whole and local buckling; this is called "Distortional Buckling".

As for the relationship between bending moment acting on members and the distortion, which is obtained by the experiment (**Fig. 10**), this Distortional Buckling is reproduced by a buckling analysis program based on Finite Strip method and it provided accurate reproduction results.

When the fulcrum length of the member (= buckling length) is changed, **Fig. 11** shows the results of using buckling analysis to compare member endurance and experimental values obtained by buckling analysis. Although endurance greatly declines with greater buckling length in the endurance evaluation formula of Japan Construction Society, where sectional binding effects from plywood are not considered, the use of plywood binding can limit the reduction of member endurance. The results from analysis of Distortional Buckling can closely reproduce member endurance corresponding to changes in buckling length.

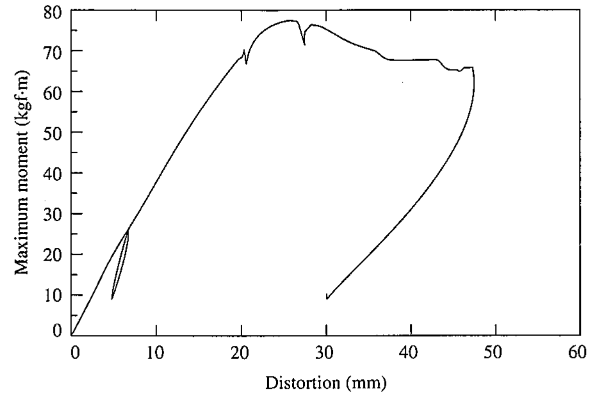

Fig. 10 Relationship between bending moment put on member and distortion

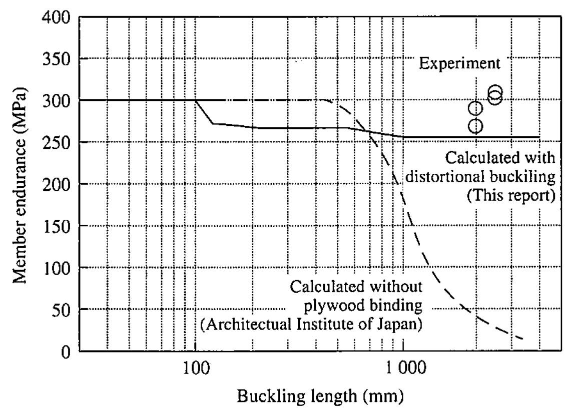

Fig. 11 Evaluation and experimental values of member endurance considering distortional buckling

The above work has been able to establish design techniques not yet undertaken even by Japan Construction Society, that is, a quantitative grasp of the binding effects of plywood member sections.

The steel thickness of rafter members when not considering plywood binding is about 1.6 mm, and by evaluating the design techniques established in this consideration, a reduction in board thickness of up to 1.0 mm, a decrease of about 38%, is possible. Since rafters account for about half of the roof framing for this development, the establishment of this design technique can lighten as much as 19% per house.

2.3.1.3 Development of joint method ensuring work productivity

Conventionally, the joint methods for thin plate members are screws, rivets and calking. This system utilizes a "one bolt" method (**Photo 2**) as the joint most emphasizing work productivity at the site. It is highly possible to have local buckling in areas where a concentrated load acts on a thin plate member. The load that has flowed to the thin plate member flows to other members through the bolt, so especially in the case of one bolt, a device that promotes load dispersion and prevents local deformation is necessary.

The idea is, therefore, to restrain local buckling of thin members at joints by inserting bolts between the thin plate member and joint hardware and fastening them with a specified tightening force. Specifically, in the case of joints for general load, the method in **Fig. 12** is used. When the load to be born is bigger, the buckling suppression effects of the thin plate member can be increased by making the bolt washer bigger.

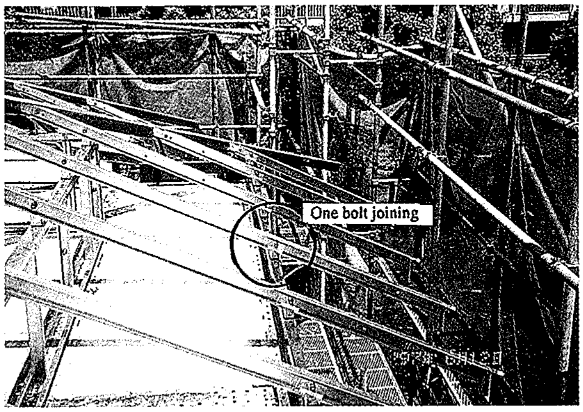

Photo 2 One bolt joint of rafter, main house panel and wall girder

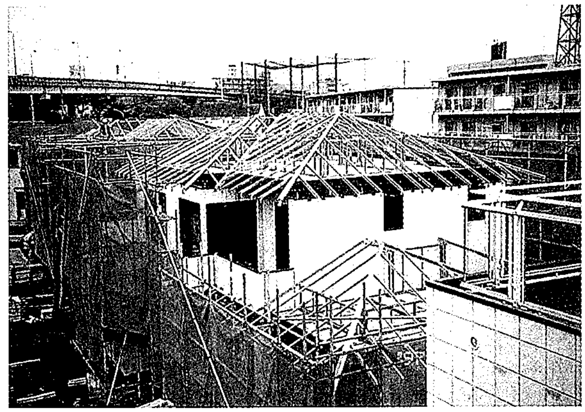

Photo 3 Scene of workability verification test

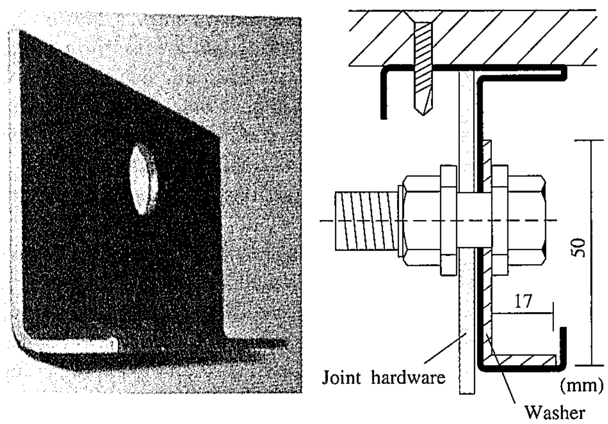

Fig. 12 Joining method in the case of big load which has to be born

2.3.2 Evaluation of "Making kits of the roof framing parts" by aseembling test

Through work verification tests (**Photo 3**) prior to specification standardization of the roof framing kit and construction of model demonstration houses at each place before product sales, the present framing system is evaluated, to confirm the four advantages. These are the initial aims.

(1) Significantly shortened work period

The conventional roof framing system using wood requires four days, but using kit parts which incorporate devices everywhere such as one bolt joints, assembly can be completed in one day. And in the conventional wooden system, after scaffolding men assemble the steel-frame body, carpenters enter the site to assemble the roof framing. This system enables work by scaffolding men, following the steel body, which can shorten the work period by around ten days overall as a result of ensuring work continuity.

(2) Quality improvement and stabilization

With this roof truss framing using zinc thin plates as material, the finished dimensional precision and quality are improved over wooden structures assembled using natural material. Although the conventional system has varying quality depending on carpenters' skills, the present system using kit parts manufactured at factories confirms that even using workmen without special skills quality is easily ensured.

(3) Significantly less weight

The effects of design that draw out the characteristics of steel with its high strength and rigidity while also optimizing rafter sections, which was an objective of this development, the weight is less than 40% of the conventional wooden roof framing, a significantly lower weight.

(4) Reduction in work costs

Along with the significant reduction in work period, this system enabled the use of workmen with no special skills, and as a result the roof framing kit leads to a reduction in the number of carpenters and a lower price per carpenter, which in turn reduces the work costs.

3. Establishing System for Production of Roof Framing Kits

In order to link realistic achievements after sales with the advantages of making kits for the roof framing, which has been confirmed in the work tests ahead of product sales, a production system providing both quality and cost competitiveness must be established. Technical targets and development in establishing a production system are discussed next.

3.1 Technical targets as a result of establishing manufacturing techniques

In recent housing construction, following the social trend of "emphasis on individuality for space," demand is increasing for free design layouts that ensure spatial freedom or larger living rooms. To analyze these social trends on the part of housing supply, it is indispensable to solve two contradictory technical problems: building production with wide variety and small numbers, and building mass production ensuring quality and cost competitiveness.

3.1.1 Building production system for producing wide variety and small numbers

Pre-fablicated house requires over 10,000 parts, big and small in all, per house. The conventional basic production system is to use advance prospective production (abbreviated inventory production hereinafter) which deals with high frequency of supply and production after taking orders because of the existence of the numerous parts. Coexistence of these two production systems causes following potential problems: complicated production instructions since they are divided into two systems, inventory production and ordered production, necessity of warehouses to store the inventory, need for putting inventory and ordered products into one shipping unit, and occurrence of accumulation due to differences between inventory production and actual shipment.

Based on these problems in the conventional system, including the trend toward wide variety and small numbers production surrounding the recent housing industry, and the surging development of information and communications networks represented by the Internet, the possibility was considered of building a production system in which only parts with manufacturing instructions from the ordering side can be quickly produced and correctly shipped between multiple companies.

Fig. 13 shows the production control system built. This totally changes the conventional production system of voucher control and inventory production and links everything, from taking product orders to shipping by information network, all of which are oriented toward a completely paperless system. This linkage by information network of Asahi Chemical on the ordering side and Sanko Metal, which is in charge of production, can realize what is called a virtual factory where Sanko Metal in effect functions as the factory branch of Asahi Chemical.

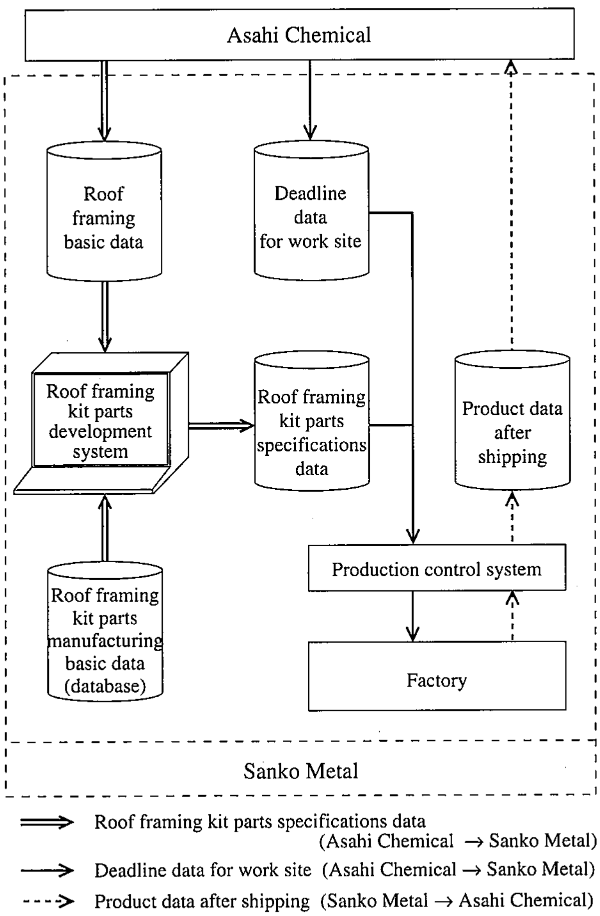

Fig. 13 Production control system

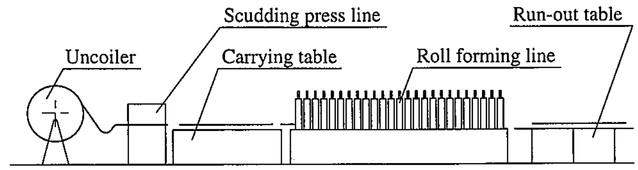

Fig. 14 Outline of mass production ensuring quality and cost competitiveness

3.1.2 Building mass production ensures quality and cost competitiveness

The roof framing kit parts are characterized by the high process precision required for member section forms and length and joints, along with the variety of parts. Generally the productivity is low when wide variety in small numbers type production as well as high process precision are required. Thus, the concept of production systems should be changed. On the assumption that computer-controlled production is available, a new production system was developed, in which a slit coil stage requiring working into precise form and cutting into predetermined length and a roll forming line assuring mass production effect were combined without a break. **Fig. 14** shows the actual production line. In particular, the slit coil stage, which is important for ensuring wide variety and small numbers production and product precision, is designed to integrate scudding lines and press lines.

Thus, a new production line was put into operation in February 1998 that ensures wide variety and small numbers production, quality and cost competitiveness and overcomes large problems of mass production. The newly developed system, amid the deepening housing depression, is credited with reduced costs and improved productivity, and its production is steadily increasing.

4. Summary

Amid deepening problems of aging construction workers and labor shortage, system development realizes lower costs and improved productivity at work site. This innovative system development can indicate an appropriate archetype for the future direction of housing development.

5. Acknowledgements

This system is jointly developed and the actual machine is made by Mr. Michio Baba, Mr. Takao Koyama, Mr. Toshiharu Maekawa, Mr. Manabu Sonobe of Product Development Dept. of Asahi Chemical and Mr. Shigenobu Kitamura in charge of building production System of Sanko Metal. We would like to thank those involved for their enthusiasm and efforts.