QUAKE RESISTING DESIGN OF COMPOSITE STRUCTURES IN JAPAN

by
T. Naka *
M. Wakabayashi **
S. Takada ***

Definitions

In this paper, the following expressions have the meanings hereby respectively assigned to them, that is to say:

"Composite structure" means a type of structure composed of steel skeleton clad with reinforced concrete. The strength of the structure is designed in expectation of the collaboration of them. (see Photo. 1-4)

"Steel skeleton" means steel frame composed of beam members and column members. They have not always balanced with areas or stiffenesses. "Reinforced concrete" means concrete reinforced by reinforcement of round steel bars.

Introduction

A composite structure is a structural design where the steel skeleton is encased with reinforced concrete and designed so as to work as a united body. The majority of buildings over six stories high in Japan are of this type.

This type of structure originates through the experience of Kanto Earthquake which happened on Sept. 1, 1923. The multi-storied buildings of those days were mainly built of steel skeleton encased with bricks called the "curtain wall system" and were considerably damaged from the quake due to failure of the outer encasement of bricks. Photo. 5 and 6 show examples of the damage. On the other hand, structures of steel skeleton encased with reinforced concrete designed with proper diagonal bracings and seismic resisting walls were hardly damaged at all. Photo. 7 is an example of this type of structure. Thus, the fundamantal course for seismic resisting structures has been standardized to this type of structural form currently called the composite structure.

The original sectional form of composite structural members is shown in Fig. 1 where the columns and beams were made of H-columns and I-beams. Thereafter, a built-up section of angles and plates as shown in Fig. 2 and 3 has begun to be mainly used for steel skeleton, due to the following reasons.

1. Although the strength of the encasing concrete was ignored, in early days it has been eventually taken into consideration due

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* Professor, Univ. of Tokyo, Tokyo.
** Assist. Prof., Univ. of Kyoto, Kyoto.
*** Assist. Prof., Chiba Univ., Chiba.

to the fact that the concrete web action has a great influence on the strength of the frame. For this reason, the open web system has begun to be mainly used for the web structures of steel skeleton columns and beams. (see Fig. 4)

2. In order to enforce the resistance of horizontal force, consideration has been made to increase the rigidity of the framework. In this connection, in order to increase the rigidity of the connection joint of the beam and column, a single gusset plate as shown in Fig. 5 has been adopted. (Explanations in detail will be made hereinafter in a latter item).
3. For the building to resist earthquakes from all directions, the column section must be designed to resist the bending moment of both principal axes.
   The column sections shown in Fig.3 are examples with such conditions in consideration and the use of built-up sections deems most adequate for such cases.
4. Steel skeleton structure designed with built-up section has more flexibility in designing and also saves material.

Steel material required per 3.3m² for 7-9 story buildings as seen from the past statistics (1) is shown in Fig. 6.

As compared to the 0.3-0.4t required prior to Kanto Earthquake, it has greatly increased to 0.5-1.0t showing a great change in structural design due to the earthquake experience. Again, it has decreased to 0.3-0.6t after the 2nd. World War and the current average tonnage is about 0.4-0.5t. Furthermore, the ratio between the amount of steel skeleton and the total amount of steel (inclusive of steel skeleton and reinforcement) is shown in Fig. 7. It shows that the use of steel skeleton are decreasing and reinforcement increasing. At the present, steel skeleton occupies about 50-60% of the total amount of steel and reinforcement occupies the rest.

As described above, this type of structure is changing to reinforced concrete from the former steel frame structure and may be said to resemble reinforced concrete rather than steel frame structure.

Experimental test shows that the strength of this type of structure can be calculated with the reinforced concrete theory, assuming the steel skeleton sectional area to an equal reinforcement sectional area, and it was learned that the strength is virtually equal to reinforced concrete structure (2) (3).

The superiority of this type of structure against earthquakes is that it has greater toughness than reinforced concrete at the failure. It is due to the reason that being rigidly jointed at the connection **joints of columns and beams and also the flanges of members being rigidly jointed by means of welding and rivetting, there is a great advantage of the** steel skeleton structure to withstand the loads even after the concrete gives way partially. This advantage can be clearly seen during the shear failure. Experiments show that when the sectional area of flange exceeds 3% of the sectional area of the concrete, it still has enough strength even after the deformation reaches 10 times the ultimate deformation of reinforced concrete. Another advantage for earthquake resisting capacity is that, there are no slipping off nor breaking of anchorage of steel skeleton as in reinforcement.

STRUCTURAL DESIGN OF COMPOSITE STRUCTURES

Multi-storied buildings of composite structures are designed in a continuous frame. A typical example of steel skeleton and reinforced concrete frames are as shown in Fig. 8a and 8b, respectively. Steel skeleton columns are usually set on the tie beam of footing.

In Japan, the height of buildings are limited to 31 meters by the law (4) when the large open area do not exist in the surrounding; however pent-house is not included in this limit. Therfore, 9-stories is the limit above ground level but there are no limits as to the depth.

The seismic force stress is solved by assuming that the horizontal force obtained by multiplying the lateral seismic coefficient with the sum of the live load and dead load, works on each floor level. The minimum value of the lateral seismic coefficient as determined by the law is as follows.

For heights less than 16 meters: seismic coefficient 0.2
For heights more than 16 meters: seismic coefficient 0.2 plus 0.01 or more for every 4 meters
For smoke stacks, water tanks and others in this category: seismic coefficient 0.3

The seismic action causes tremendously greater bending moment than the axial force to the usual columns. On the columns adjoining a continuous quake resisting walls, a great compressive and tensile stress will act upon it, due to the wall panel working as a bar fixed to the foundation as shown in Fig. 9. And due to the action of the wall as a bar, an up and down displacement will occur at the connection joints of the wall and beam, causing a great shearing force to work on beams adjoining the wall.

STRENGTH OF COMPOSITE STRUCTURE MEMBERS

There are three methods of calculating composite structures. The first method which had been adopted during the earlier period is calculated only by the steel skeleton and reinforcement, assuming the concrete merely as a fire resisting and buckle resisting material. The second method is done in accordance with the reinforced concrete calculation theory (the straightline theory) assuming the sectional area of steel skeleton as reinforcement. The third method is calculated by the sum of each respective allowable strength of steel skeleton and reinforced concrete. The standard calculation method of The Architectual Institute of Japan (AIJ) (5) adopts the third method and uses the second method as a subsidiary method. The characteristic of this method is in calculating the strength of steel skeleton and reinforcement on seperate basis and thereby obtaining a larger allowable strength than by the calculation of reinforced concrete theory alone.

1. Section of beam (Fig. 10)

$M_a = {}_sM + {}_rM$ ....(1)

M_a = Allowable bending moment

${}_sM$ = Allowable bending moment for steel skeleton portion $= {}_sa_t \cdot {}_sf_t \cdot {}_sj$

${}_rM$ = Allowable bending moment for reinforced concrete portion (by the straightline theory)

${}_sa_t$ = The effective sectional area of steel skeleton flange

${}_sf_t$ = Allowable tensile unit stress of steel skeleton

${}_sj$ = Distance between the gravity centre of steel skeleton flanges.

2. Section of column

When $\left.\begin{array}{l} N \leqq {}_rN_c \\ N_a = {}_rN \\ M_a = {}_sM + {}_rM \end{array}\right\}$ ....(2)

When $\left.\begin{array}{l} N > {}_rN_c \\ N_a = {}_sN + {}_rN \\ M_a = {}_sM \end{array}\right\}$ ....(3)

N = Working axial compression

N_a, M_a = Allowable axial compression and allowable bending moment, respectively

${}_sN$, ${}_sM$ = Allowable axial compression and allowable bending moment for steel skeleton portion

${}_rN$, ${}_rM$ = Allowable axial compression and allowable bending moment for reinforced concrete portion (by the straightline theory)

${}_rN_c$ = Allowable axial compression when the reinforced concrete portion is subject to axial compression

For the calculation of reinforced concrete, the allowable compressive unit stress shall be decreased as indicated below, for the reason that when the steel skeleton increases, the circulation of the concrete will be deterred therefore causing a decrease in the effective sectional area.

$f_c' = f_c(1 - 15 \cdot {}_sP_c)$ ....(4)

f_c = Allowable compressive unit stress for concrete

${}_sP_c$ = The Ratio of steel area of the skeleton subjected to compressive stress to the gross sectional area of the column

The above equation has been formed in accordance with each respective characteristic of the steel skeleton portion and reinforced concrete portion; the former mainly carrying the bending and the latter the axial compression force. The stress of columns due to earthquakes being mainly bending, it seems effective to enlarge the steel skeleton for quake resisting purpose.

The allowable strength of equation (1)-(3) nears the ultimate strength when steel skeleton increases in comparison to reinforcement and nears the strength obtained from the straightline theory when it decreases.

3. Calculation for shear and bondage

When the nominal shearing stress $\tau = Q/\frac{7}{8}d$ of concrete exceeds the allowable shearing unit stress, the allowable shear shall be calculated as shown below.

$Q_a = {}_sQ + {}_rQ$ ....(5)

Q_a = Allowable shearing force
${}_sQ$ = Allowable shearing force for steel skeleton portion
${}_rQ$ = Allowable shearing force for reinforced concrete portion

${}_rQ$ is the shearing force calculated by the usual reinforced concrete theory with stirrups and concrete. When the web of steel skeleton is vertical tie plate type (see Fig. 4a), calculation shall be done by assuming the tie plate as stirrups and thus ${}_sQ = 0$.

The bond unit stress of the steel skeleton and reinforcement will be calculated by the following equation for working shearing force Q.

Steel skeleton $${}_s\tau_b = \frac{Q \cdot \frac{{}_sa_t}{a_t} - {}_sQ}{{}_r\psi \cdot \frac{7}{8}d} \qquad \text{.............(6)}$$

Reinforcement $${}_r\tau_b = \frac{Q \cdot \frac{{}_ra_t}{a_t}}{{}_r\psi \cdot \frac{7}{8}d} \qquad \text{.............(7)}$$

${}_sa_t$, ${}_ra_t$ = Sectional area of steel skeleton and reinforcement, respectively, on the tensile side
a_t = Sectional area **of the total steel** at tensile side
d = Distance between the compressive surface and gravity centre of the total tensile steel
${}_s\psi$, ${}_r\psi$ = Perimeter of the steel skeleton and reinforcement, respectively, at the tensile side

According to an experimental test, bondage strength per unit surface area of steel skeleton is approximately 1/2 that of plain round bar (2). In this type of structure, since there are no special attachment of dowels as on the common composite beams for the prevention of slipping, there may be lack of bondage strength. On such instances, web plates or diagonal member shall be strengthened and the shearing force shall be directly conveyed by the web structures of steel skeleton. Equation (6) is derived from these conditions in consideration.

Shear failure of members may be seen in the records of the Kanto Earthquake and since it has a great influence for an earthquake resisting capacity, the allowable shearing force has been taken on a much lower value than that derived from the experimental test to avoid unfavorable shear failure of the members.

DESIGN OF CONNECTION JOINTS BETWEEN BEAMS AND COLUMNS

Since the connection of the beam and column is subject to considerable influences of bending moment from earthquake, it is very likely to cause wide cracks and also to be damaged due to partial compressive destruction of concrete. For this reason, strong and rigid type of joints must be considered. Generally, in reinforced concrete structure, a rigid connection may be comparatively easily obtained due to its continuous structure, but in composite structures, if the rigidity of the connection of steel skeleton is weak, the concrete may collapse before the steel skeleton commands its strength capacity. For example, experimental test revealed that when concrete encases the connection joint of the steel skeleton as shown in Fig. 11 a large crack unpermissible for general use will occur before the connection joint of the steel skeleton reaches its allowable resisting capacity.

When rivets are used, the typical Japanese method of jointing steel skeleton is as indicated in Fig. 12. In such instances, all the rivets will be subjected to only the shearing stress, so that the rigidity of the connection joints may be reliable.

When the excessive stresses occur at the extreme fibre of the gusset plate, a top angle may be attached (see Fig. 13). However, since tensile stress works on the rivet, it is used as a subsidiary material.

Recently, in order to increase the rigidity of the connection joints, welding is occasionally used. Fig. 14 shows a typical welding joint. The flange of beam is butt welded to the column.

Fig. 15 shows another instance where the columns are connected to the continuous beams. It was designed as to easing the designing condition of welding joints from the view point that the tensile stress of the flange of the steel skeleton occuring from the bending moment will be reduced by the axial compression which works on the column.

Care must be taken at the connection joint of beams and columns as it is subject to bending moment from seismic force as shown in Fig. 16. In such inctances, as the shaded portion which is a common portion of the beam and column is subject to shear, the concrete at this portion has considerable influence on the strength of the connection joint. Therefore, it is important to consider a connection which enables concrete to flow freely. For example, as is shown in Fig.14 & 15, when concrete cannot flow due to the horizontal diaphragm,it is required to place a comparatively thick web plate to resist in lieu of the concrete.

Fig. 17 shows a similar type to Fig. 14 considering the flow of concrete. Fig. 17(b) shows a vertically placed stiffener and although stress concentration occurs when the tensile stress of the beam flange is conveyed to the column, if the thickness of the column flange is equal to or larger than that of the beam flange, experimental test revealed that it is of no important matter concerning the problem of strength (6).

Bond failure and shear failure may occur due to the shear which works on this portion, but as for the latter, it is of no important matter unless the width of the concrete is extremely small. The bond failure may cause partial destruction of concrete at the compressive side of Section A-A indicated in Fig. 16 and care must be taken to avoid this. A counter measure for such instances may be done by connecting the beam flange and column with as much rivets and welding as possible. In other words, as it is a matter of concrete to flow freely and to avert the bond failure, the connecting gusset plate of

Fig. 12 may be alternated to that of Fig. 18. Experiments are recently being done on simplifying of such steel skeleton connection joints.

The allowable strength of the connection joints is calculated by the sum of the steel skeleton and reinforced concrete portion, similar to beams and columns.

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(3) S. Takada, " A Study of Steel-framed Reinforced Concrete Failing in Shear ", Research Reports of Faculty of Technology, Chiba Univ., Vol.10, No. 17, March 1959. (in English)

(4) Building Standard Law, Enforcement Order.

(5) AIJ Building Code for Composite Structure (1958).

(6) T. Naka, H. Saito, "Studies of All-welded Steel Construction (No. 7) ", Research Report of AIJ, No. 43, June 1958. (in Japanese)

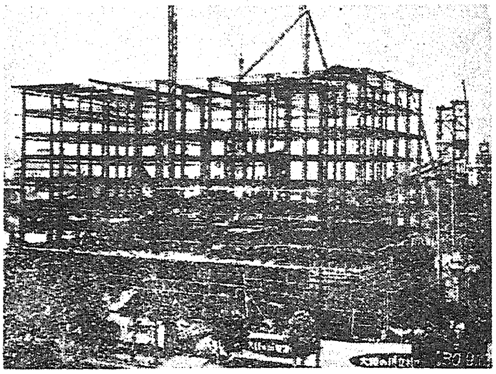


Photo. 1

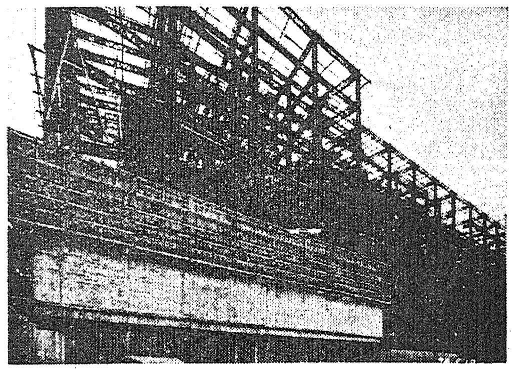


Photo. 2

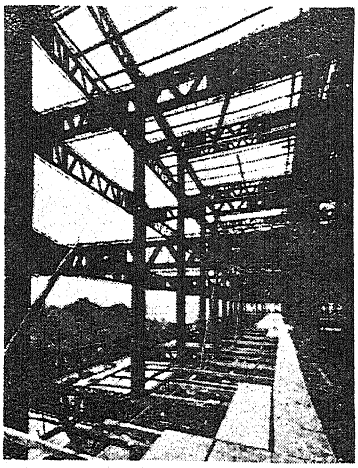


Photo. 3

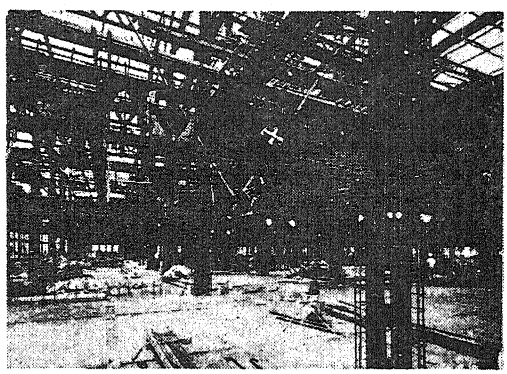


Photo. 4

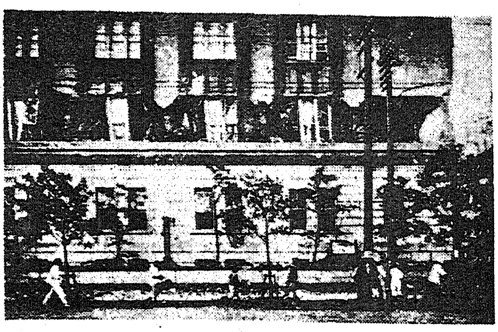


Photo. 5a

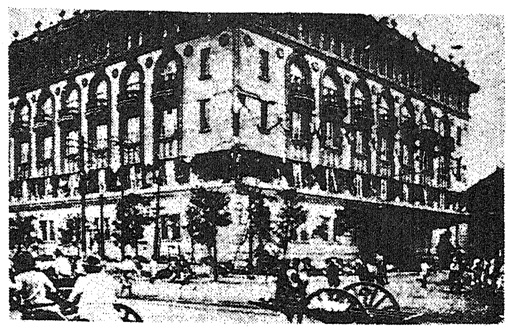


Photo. 5b

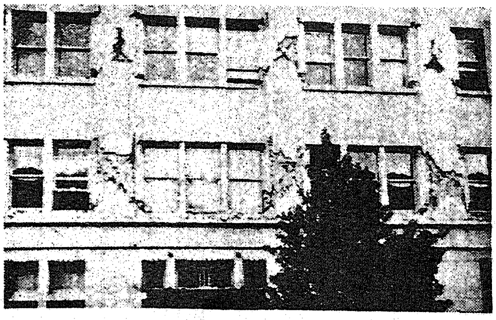


Photo. 6

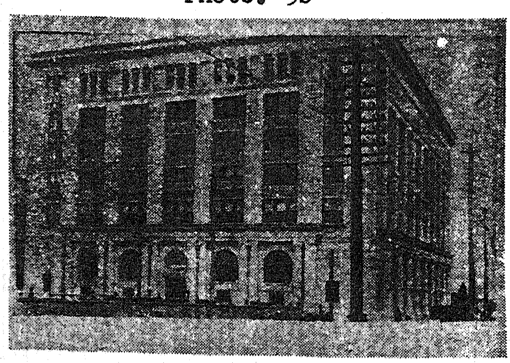
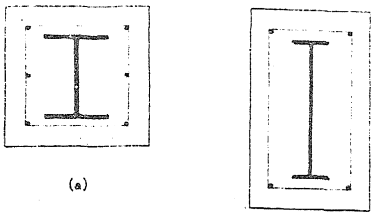
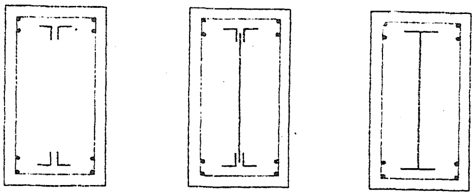


Photo. 7



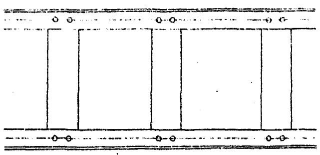
(a) (b)

Fig. 1 Original type of sections of members
(a) Section of column
(b) Section of beam

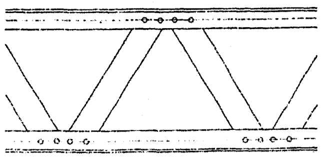


(a) (b) (c)

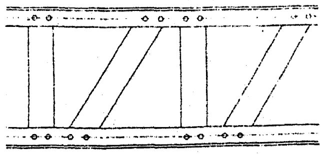
Fig. 2 Type of beam sections currently used



(a) Vertical tie plate type

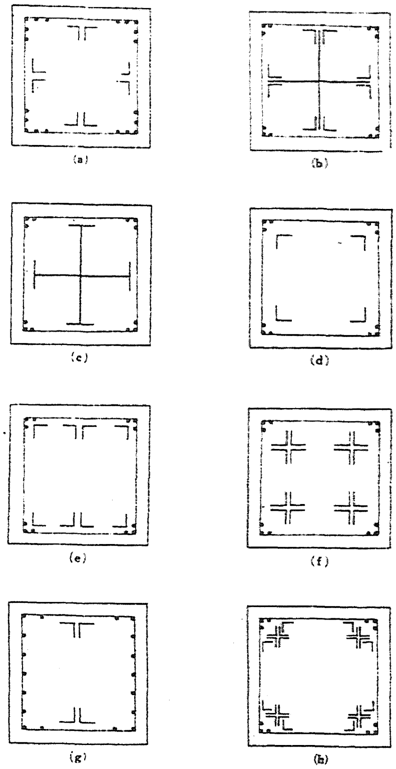


(b) Warren type



(c) Pratt type

Fig. 4



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 3 Type of column sections currently Used

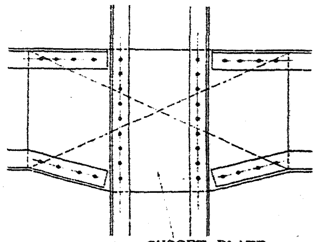


Fig. 5 Connection joint of columns and beams with a single gusset plate

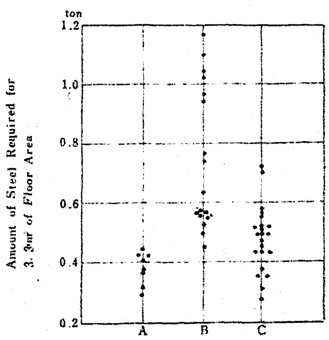


Fig. 6 A: Before Kanto-Earthquake
B: After Kanto-Earthquake
C: After 2nd War

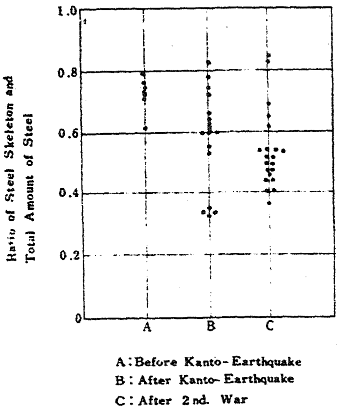


Fig. 7

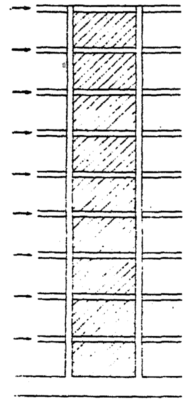


Fig. 9

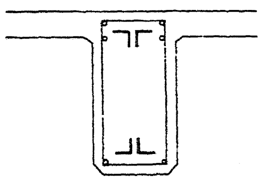
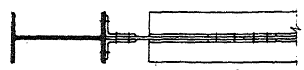


Fig. 10 Section of beam



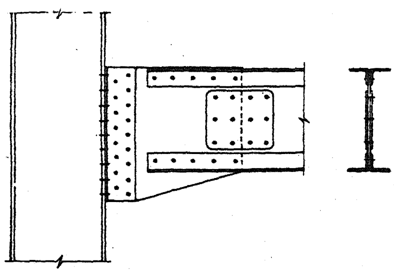
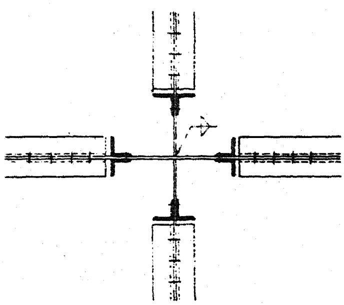


Fig. 11 Semi-rigid connection of steel skeletons (joint using clip angles)



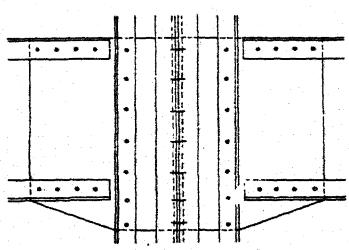


Fig. 12a Joint using gusset plate

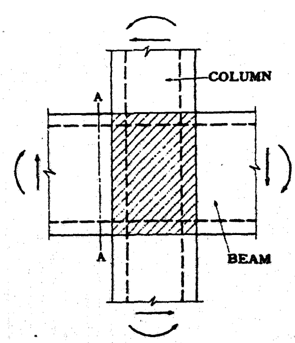


Fig. 16 Stresses at connection joints due to seismic force

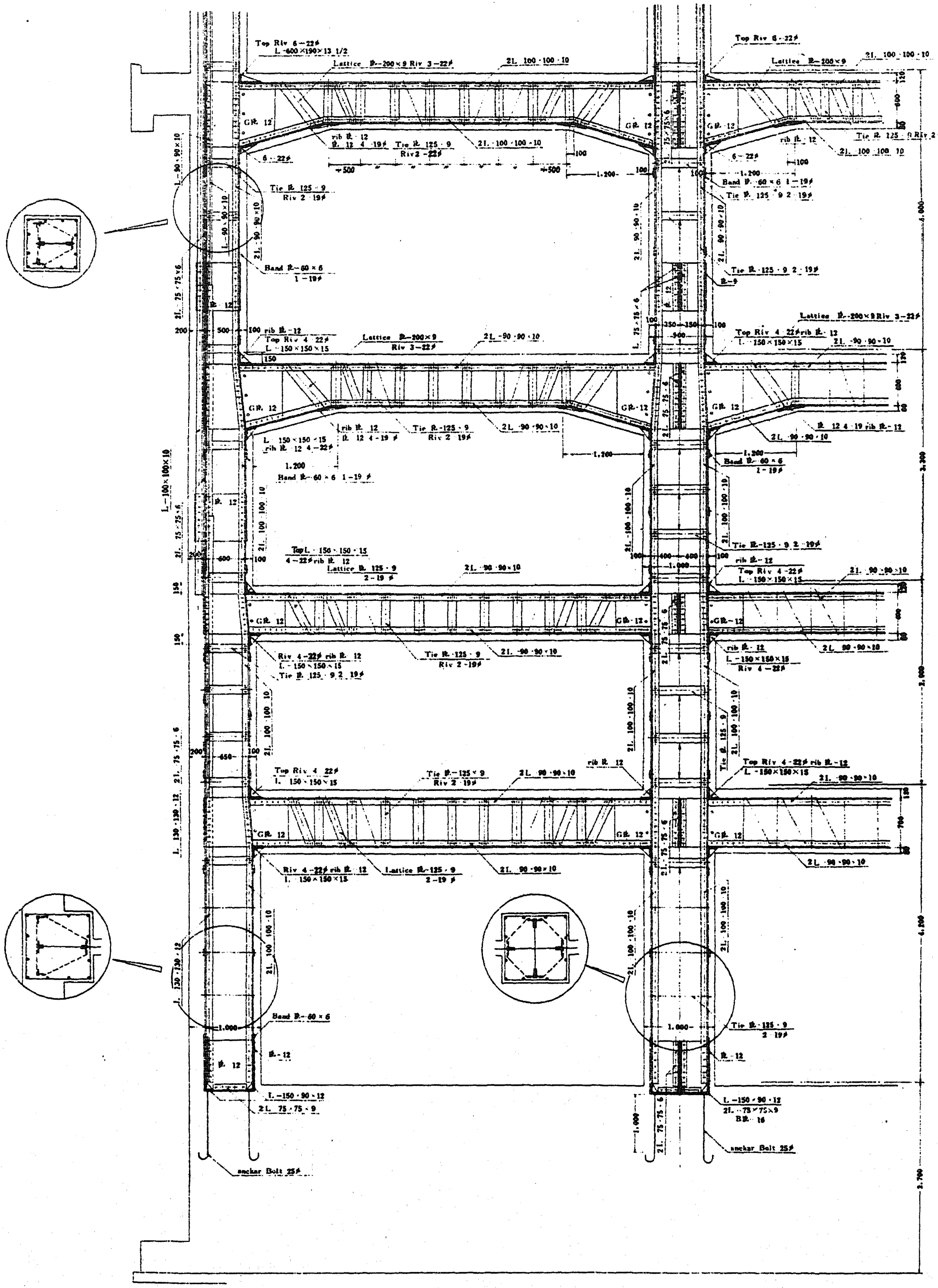


Fig. 8a Typical example of steel skeleton frame

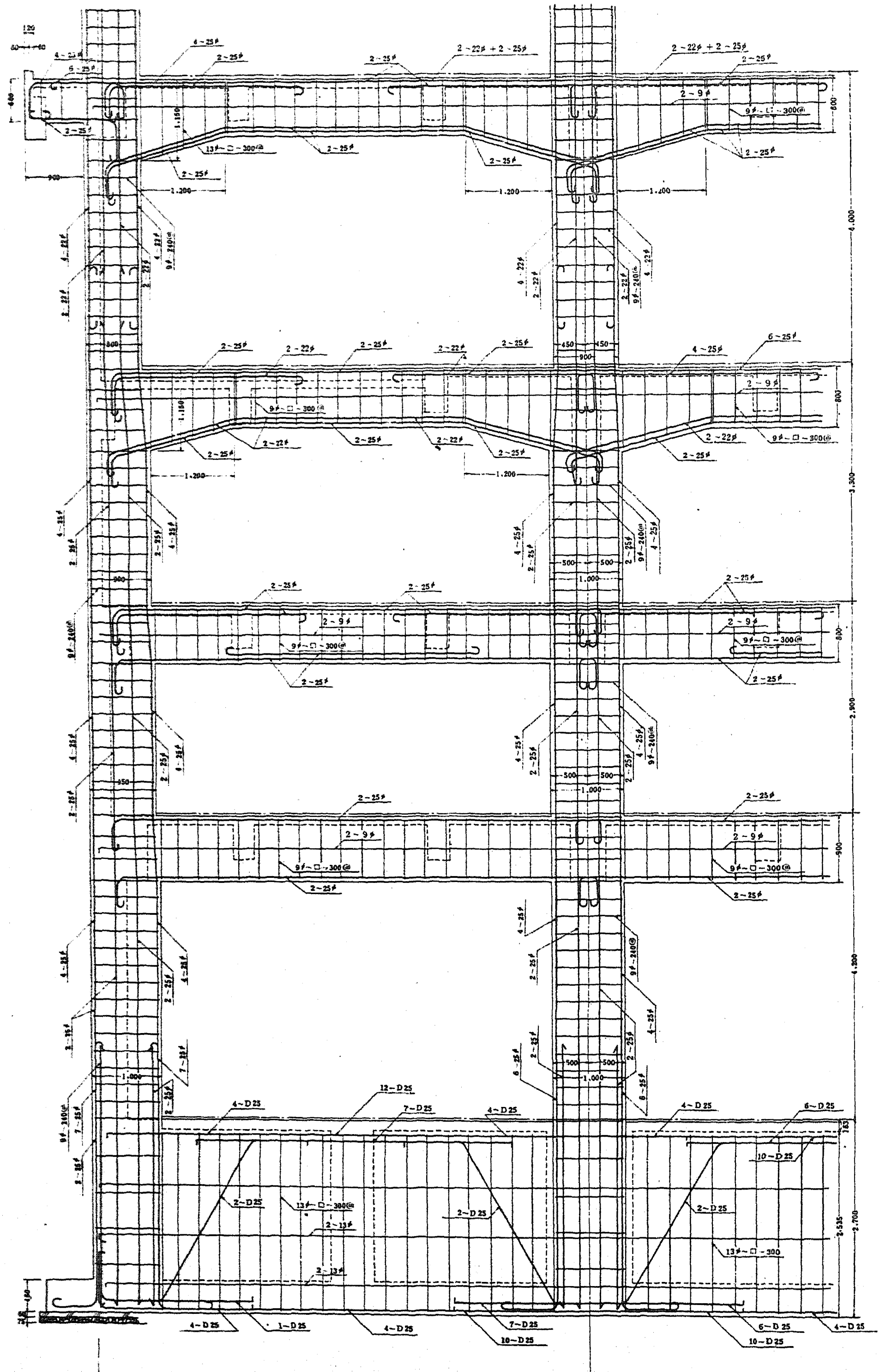


Fig. 8b   Typical exmaple of reinforced concrete frame

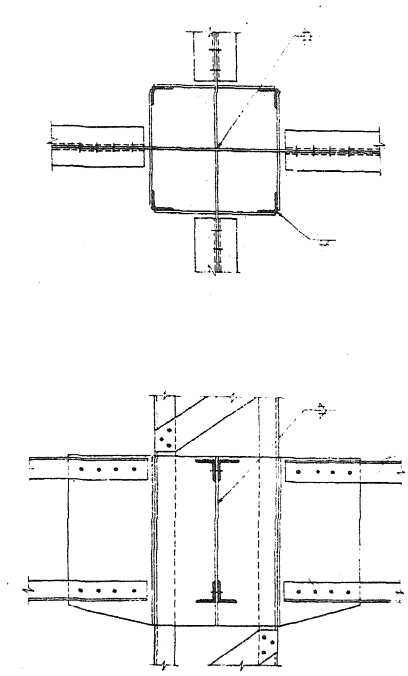


Fig. 12b Joint using gusset plate

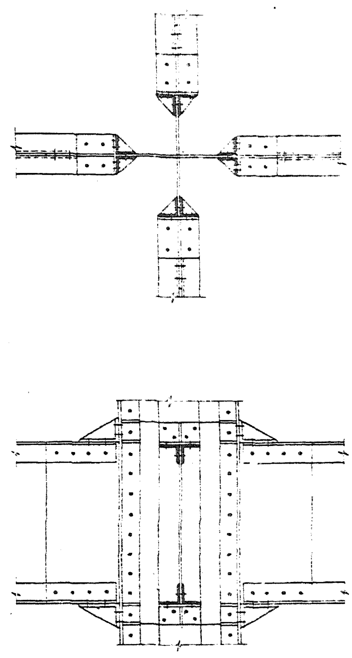


Fig. 13 Joint using gusset plate and subsidiary top angles

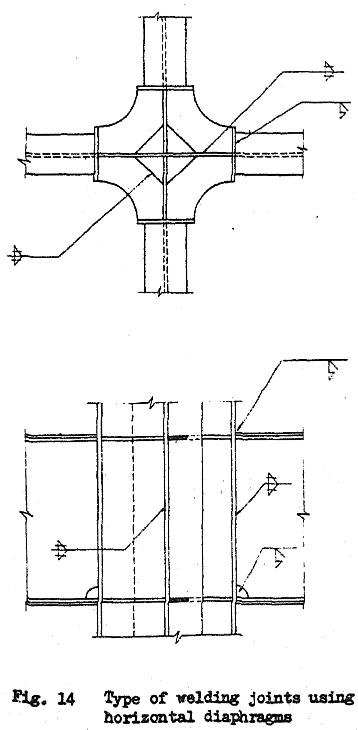


Fig. 14 Type of welding joints using horizontal diaphragms

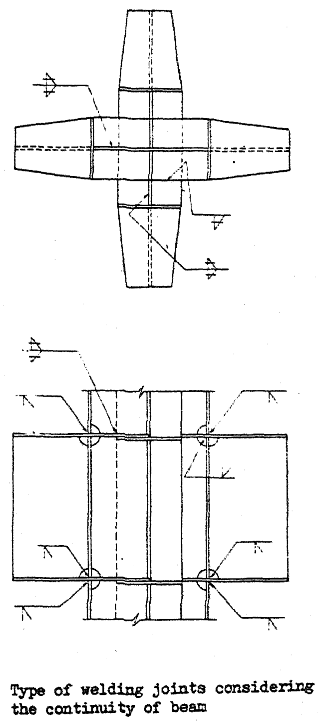


Fig. 15a Type of welding joints considering the continuity of beam

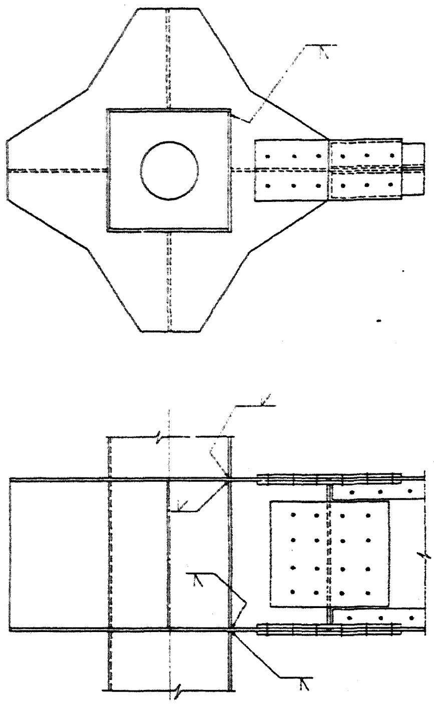


Fig. 15b Type of welding joints considering the continuity of beam

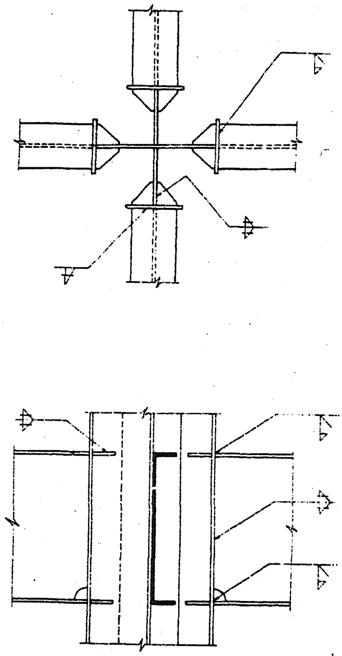


Fig. 17a Type of welding joints considering the flow of concrete

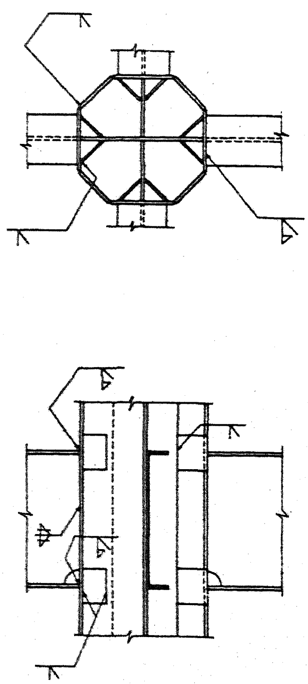


Fig. 17b Type of welding joints considering the flow of concrete

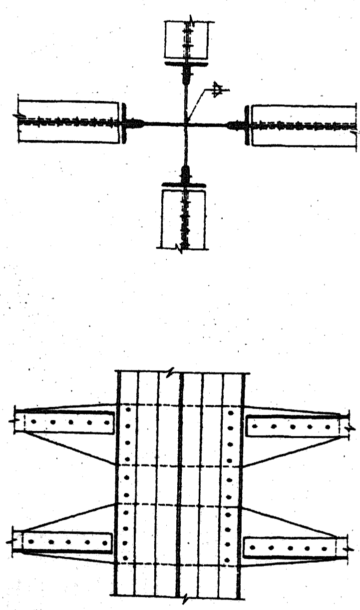


Fig. 18 Modified type of joints using gusset plate

DISCUSSION

W. P. Edwards, Edwards & Clendon Consulting Engineers, New Zealand:

In Japanese practice, plates are connected to flanges with rivets. Is there any objection to welding instead of rivets?

T. Naka, M. Wakabayashi, S. Takada:

It is more rational to connect lattice plates with flange by welding rather than by rivets, so far as the strength is concerned; chiefly from economical reason rivets are generally used.

S. Okamoto, University of Tokyo, Japan:

I appreciate your result of structural testing using the test piece of prototype scale. I would like to ask you tell me whether you recognized the scale effect of structural testing.

T. Naka, M. Wakabayashi, S. Takada:

As for the members subject to bending, compression or to the combined action or the strength of the joints of members, where any scale effect can not be recognized; it is advantageous to make a test piece in a fashion similar to the construction of a building when we rivet or weld steels or fabricate concrete members using the test piece of the prototype scale.

In case of the members subject to shearing force, the scale effect was clearly perceived: The smaller the piece is, the stronger value it showed. Therefore the scale effect must be taken into account in formulating experimental results. However beams with the depth of more than thirty centimeters showed approximately equal value or the same as that of prototype.

E. Arze, University of Concepcion, Chile:

1. How are lateral forces distributed between different members?

2. Which is the design practice for Dead Loads, to resist them with the steel frame alone or by composite action?

3. Are these buildings usually designed with shear walls, diagonal bracing or only rigid frames?

4. Is it possible to obtain figures on the weight of these buildings per unit area & comparative figures of weight of round bars per unit area for reinforced concrete buildings?

5. In these type of buildings is there any reason to prefer riveting to welding of the steel frame?

T. Naka, M. Wakabayashi, S. Takada:

1. Lateral forces are distributed according to the relative magnitude of stiffness factor of concrete section alone.

2. Members are designed assuming the composite action of the steel frame and the reinforced concrete also for dead load.

3. Most of these buildings have either shear walls or diagonal bracings.

4. Commonly used figures are as follows:

Material / Construction	Concrete (m^3/m^2)	Round bars (kg/m^2)	Steel frame (kg/m^2)
Composite(6-9 storied)	0.6	40-70	70-100
R. C. (4-5 storied)	0.6	70-100	0

5. The methods which are used in joining the steel skeleton in these buildings can be classified as follows:

(a) Riveted alone
(b) Mainly riveting with subsidiary welding
(c) Riveting except joints with welding
(d) Mostly welding and riveting is used only for joints in the field
(e) Welding only

Most buildings now employ (b) or (c), because welding is more convenient for making joints than riveting. (d) and (e) are now getting used, but those are rarely used as yet because of economical reasons.