Applications of damage-controlled structure to diagonal lattice tube building

Autor(en): **Hayashi, Kenichi / Unno, Toshio / Iwata, Mamoru**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **79 (1998)**

PDF erstellt am: **12.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-59946

Applications of Damage-Controlled Structure to Diagonal Lattice Tube Building

Kenichi HAYASHI
Structural Eng.
Nippon Steel Corp.
Tokyo, Japan

Toshio UNNO
Mgr
Alpha Structural Design
Tokyo, Japan

Mamoru IWATA
Gen. Mgr
Nippon Steel Corp.
Tokyo, Japan

Summary

This design shows an application of a damage-controlled structure to a structure having a diagonal lattice tube. The damage-controlled structure is a combination of primary structure and seismic members. This building is a diagonal lattice tube structure. The framework is exposed on the outside of the building and the floor frames are positioned inside of the diagonal lattice tube. The center portion of the diagonal lattice tube is made up of seismic members using axial hysteretic dampers. The rigidity of the entire structure, the energy-absorption initiation level, and the total amount of energy absorption are controlled by varying cross-sectional areas and materials of the seismic members. By thus decreasing the seismic responsiveness of the conventionally elastically designed, diagonal lattice tube, we have realized an economical building.

1. Introduction

This paper describes a structural design in which the concept of damage-controlled structure is applied to a diagonal lattice tube building.
The diagonal lattice tube comprises a framework of diagonal columns and a floor framing in triangles. If the diagonal lattice tube is regarded as an elastic trussed structure, it provides high stiffness for a high-rise building and the member force is of the axial force governing type. Under dynamic loads such as seismic load, however, the high stiffness induces an increase in the seismic response story shear-force and the cross-sectional area of members tends to become large.
The damage-controlled structure (Connor et al. 1997) is composed of a primary structure and seismic dampers. The primary structure constantly supports loads and behaves elastically during an earthquake. The seismic dampers absorb the input energy during an earthquake. The damage level of buildings is controlled by setting the quantity of energy absorbed by seismic dampers.
In the 1995 Hyogoken-Nanbu earthquake, the fracture phenomenon occurred in many buildings of steel-frame construction. In the high-rise housing complex "Ashiyahama Seaside Town", in particular, the fracture from the base material of extra-thick steel-frame columns posed various problems. This building is a mega-structure using a trussed structure and does not have seismic dampers for absorbing seismic input energy. On the one hand, it has become a practice since this earthquake to set an energy absorption mechanism for high-rise buildings and to examine building performance against an excessive input energy that exceeds the design load. On the other hand, the resistance of materials themselves to brittle fractures has begun to attract attention in the phenomenon where a failure occurs without the buckling of columns.
This building, planned one year after this earthquake, uses a diagonal lattice tube, which is exposed to the outside. The building is so designed that the diagonal lattice tube serves as the damage-controlled structure, and a reduction in seismic load and setting of the energy absorption mechanism are performed. Furthermore, the resistance of the members of the diagonal lattice tube to brittle fracture has been verified by tests.

2. Outline of structure

The present building has fourteen stories above ground and two below. The frame above the ground rises from the first basement. The height of the building is 63 m. The floor area of the building is 24 x 24 m above ground and 38 x 34 m underground. The structure above ground is of steel, while that underground is of SRC and RC.

The framework above ground is a diagonal lattice tube with a gradient of about 60° which is exposed outside. The floor frames are located 900 mm inside from the diagonal lattice tube. The framework and floor frames are connected by projecting members (Fig. 1).

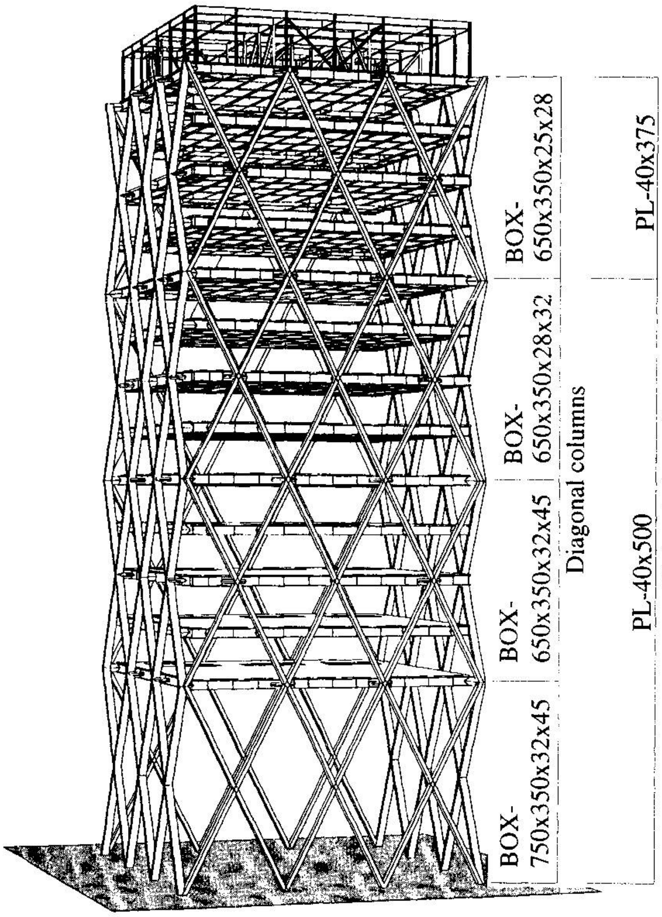

Fig.1 Framework and floor frames

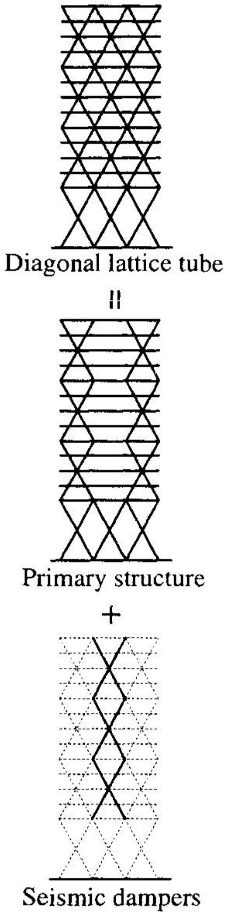

Fig. 2 Concept of seismic design

The diagonal lattice tube can be regarded as a kind of truss frame. The member force is of the axial force governing type. The concept of the seismic design of the diagonal lattice tube is shown in Fig. 2. The diagonal lattice tube consists of a primary structure and seismic dampers. The primary structure supports stationary loading and behaves in an elastic manner upon occurrence of an earthquake. The seismic dampers absorb the input energy at the time of an earthquake. The primary structure consists of the first story of diagonal lattice tube, diagonal columns at the corners, and floor frames. The other diagonal lattice tubes are the seismic dampers. For seismic dampers, unbonded members, which are hysteresis type dampers of the axial force system, are used.

In the design, the stiffness of a building can be adjusted by changing the sectional area of primary structure members and unbonded members. The level of the load at which the building starts to absorb seismic energy can be set by determining the combination of the materials and sectional areas of unbonded members.

3. Seismic design and response

3.1 Target of seismic design

The target of seismic design is to ensure that the primary structure is completely in the elastic region against an earthquake ground motion of Level 2 (50 cm/sec). For this purpose, a safety factor of 1.2 must be ensured by conducting the allowable stress design of each part using a maximum story shear-force due to an earthquake ground motion of Level 2. As with the design of general high-rise buildings, the limit of maximum drift angle is 1/200 for an earthquake ground motion of Level 1 (25 cm/sec) and 1/100 for an earthquake ground motion of Level 2.
Furthermore, a target value for an earthquake ground motion of Level 3 (100 cm/sec) is set in the present building. The load-deformation in which the members buckle and the plastic hinge occurs for each story of the principal structure is regarded as the elastic limit, and the maximum value of response to an earthquake ground motion of Level 3 must be within the elastic region. Unbonded members allow materials to become plastic under an earthquake ground motion of Level 1 or less (15 ~ 20 cm/sec). As a result, the stiffness of the building decreases and the unbonded members begin to absorb energy.

3.2 Acting direction of horizontal load and dynamic behavior of building

An examination is made into the effect of the acting direction of horizontal load on the dynamic behavior of diagonal lattice tube. In the case of the present building, the acting direction of horizontal load is in the range of 0 to 45 degrees from the X- or Y-direction in terms of plane symmetry. There is no floor framing in the first story, and there is no member that supports the diagonal lattice tube from the inside. For this reason, the effect of the acting direction of horizontal load manifests itself remarkably. A static numerical analysis of this first story is made in consideration of the nonlinearity of the stress-strain relationship of the material and geometrical nonlinearity (Fujimoto et al. 1975) when the acting directions of horizontal load are 0, 15, 30 and 45 degrees with respect to the X- or Y-direction. According to the load-deformation curves in each direction of horizontal load, the strength decreases with increasing angle with respect to the X- or Y-direction, although the initial stiffness is the same in each case (Fig. 3). In view of this point, the seismic response analysis is made in the X-direction, Y-direction and 45-degrees direction.

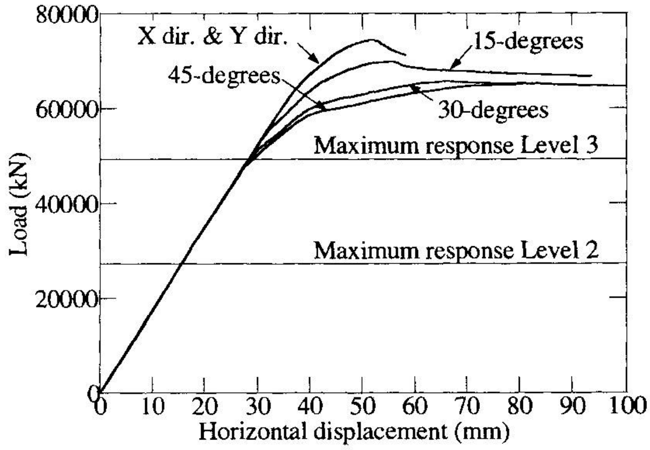

Fig. 3 Load-deformation Curve

The load-deformation curves and elastic limits of each story in the X-direction, Y-direction and 45-degrees direction are determined (Fig. 4). Buckling occurs in the diagonal columns. However, yield strength does not decrease abruptly. The hysteresis characteristics for a seismic response analysis and the elastic limit for a design target are set based on this load-deformation curve. If buckling or plastic hinge does not occur in the members before the completion of an analysis, the load-deformation upon completion of the analysis is set as the elastic limit for convenience sake.

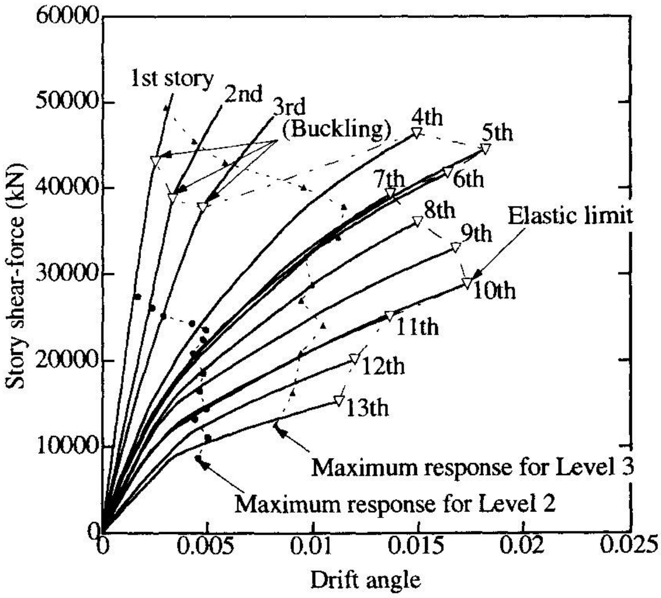

Fig. 4 Load-deformation curve and seismic response

3.3 Seismic response analysis

In the seismic response analysis, a 14 mass point system is adopted in which the floor position of the first basement of the building is fixed, and the equivalent stiffness of flexural-shear beam model is used.
The first natural period of this mass system is considerably short compared with general

buildings of steel-frame construction (building height x 0.03 = 1.8 seconds) and this building has high stiffness (Table 1).

Table 1 Natural period of the mass system

	X dir. & Y dir.		45-degree	
	in elastic region	all unbonded members yielded	in elastic region	all unbonded members yielded
1	0.958	1.406	0.980	1.414
2	0.387	0.540	0.408	0.550
3	0.263	0.333	0.336	0.364

The earthquake ground motions for the response analysis are the four motions of El Cento, Taft, Tokyo and Hachinohe.
This earthquake response analysis is made by paying attention to changes in the natural damping that has a great effect on the damping of the building and those in the stress-strain relationship of the energy absorbers of unbonded members.
In buildings of steel-frame construction, the natural damping coefficient is generally 2%. In the present design, however, responses when the natural damping coefficient is 1% and 0% are also determined and the effect of the damping by unbonded members is verified. The damping matrix of natural damping is assumed to be proportional to the stiffness. The shear stiffness by unbonded members is excluded from the shear stiffness matrix used to prepare the damping matrix.
For the low yield point steel plate LYP100 that is the energy absorber of unbonded members, the yield point intensity is basically set at 100 N/mm^2. The stress-strain curve shows changes in such a manner that, for example, the yield point increases 1.6 times when the temperature drops from 0°C to –40°C, and it increases 2.3 times when the strain rate increases from 0.02%/sec to 100%/sec (Nakamura et al. 1997). For this reason, four types of hysteresis characteristics of unbonded members in which the yield point intensity is 30, 60, 100 and 200 N/mm^2 are set, and the scatter of analysis is examined (Fig. 5).

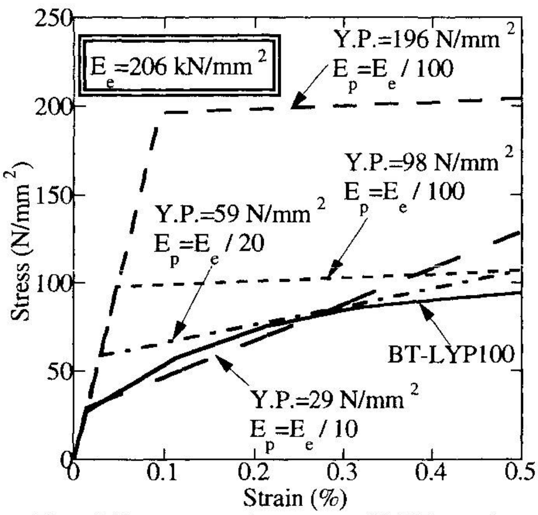

Fig. 5 Stress-strain curve of LYP steel

The yield stress intensity of LYP-100 is set at 100 N/mm^2 in the response analysis made using the natural damping coefficients of 1% and 0%, and the natural damping coefficient is set at 2% in the response analysis made using the yield point intensities of LYP-100 of 30, 60 and 200 N/mm^2.
Even with the same input earthquake ground motion, the value of response changes depending on the magnitude of natural damping. The response values of Hachinohe wave have a relatively small scatter and show the absorbed energy distribution of each story. When the natural damping coefficient is 2%, the energy absorption by the first story that has high stiffness is large. This energy absorption by the first story is gradually replaced with the energy absorption by unbonded members as the natural damping decreases (Fig. 6). Also, the maximum drift angle increases with decreasing natural damping (Fig. 7).
The maximum drift angle for each stress-strain curve of LYP-100 is shown in (Fig. 8). There is scarcely any difference at Level 1. This is because the unbonded members scarcely yield. The scatter of response increases with increasing level of input earthquake ground motion. The greatest

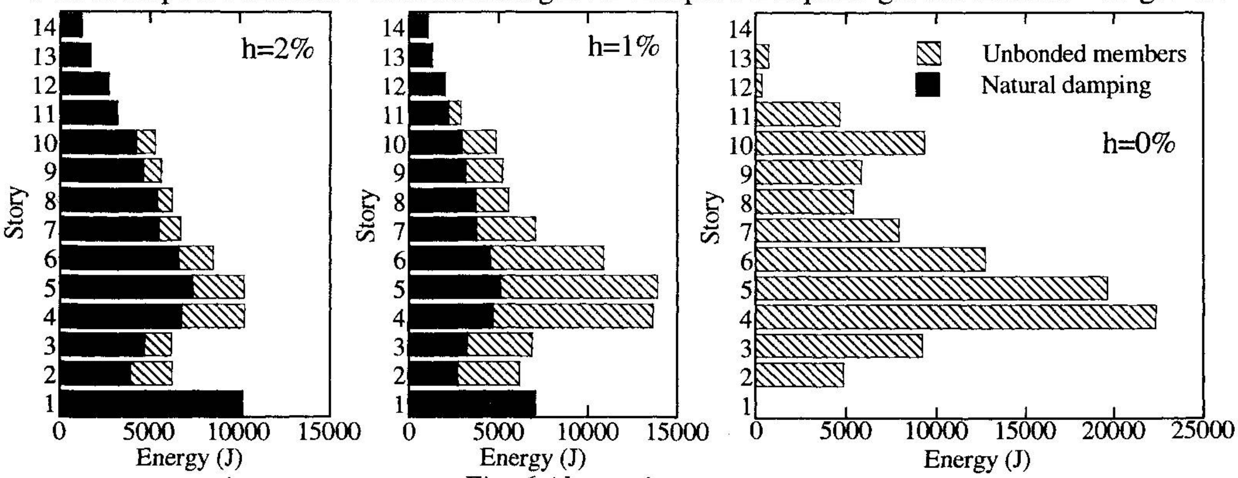

Fig. 6 Absorption energy

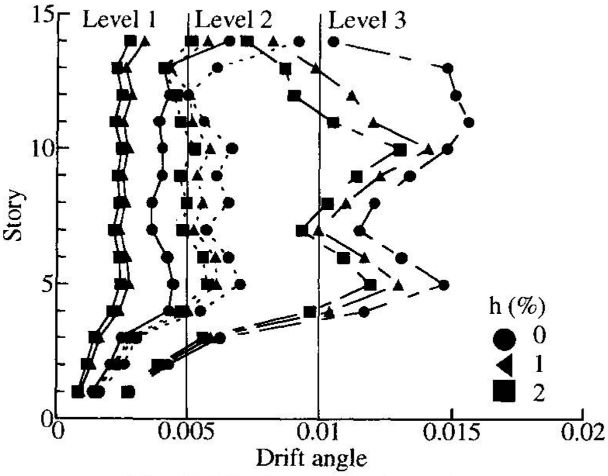

Fig. 7 Maximum drift angle

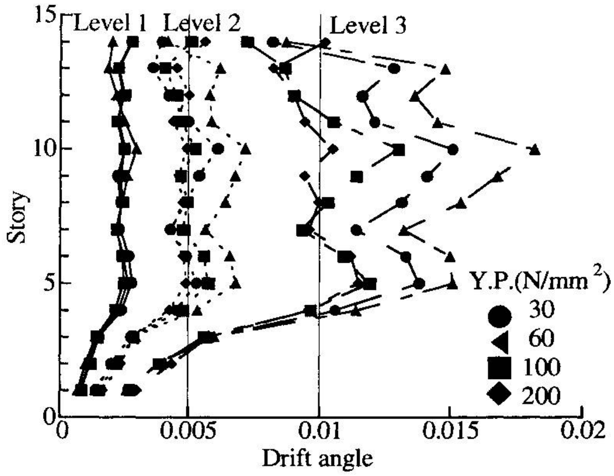

Fig. 8 Maximum drift angle

response is obtained when the yield point is 60 N/mm^2.

When the yield point is 100 N/mm^2, the maximum drift angle is 1/336 for an earthquake ground motion of Level 1 and 1/173 for an earthquake ground motion of Level 2.

The story ductility factor of maximum response, which is the ratio to the elastic limit, is 0.38 for an earthquake ground motion of Level 1, 0.68 for an earthquake ground motion of Level 2, and 1.2 for an earthquake ground motion of Level 3. For an earthquake ground motion of Level 3, the diagonal columns in part of the second story reach the buckling load in the input in the X- and Y-directions, and those in part of the first- to third stories reach the buckling load in the input in the 45-degrees direction.

The allowable stress design of each part is conducted using the story shear-force of maximum response to Level 2.

4. Diagonal lattice tube joint

Large tensile force is induced in diagonal columns upon occurrence of an earthquake. The temperature of these columns, however, drops in winter. It is, therefore, necessary to use a steel with high brittle fracture resistance for these columns.

Charpy absorption energy is used as an indicator of brittle fracture resistance. For SN and TMCP steels, this energy is specified to be higher than 27J at 0°C. According to the transition curve of HT325C-FR, for TMCP steel, used for the present building, the Charpy absorption energy is more than 280J at 0°C and its transition temperature is below -50°C. Simply put, this steel has a performance which is far higher than the specifications. SN steel also exhibits high performance.

The steel used for the diagonal columns has excellent brittle fracture resistance. According to the transition curve of the steel casting used in the joint, however, the Charpy absorption energy is higher than 100J at 0°C, but the transition temperature is about 0°C. The steel casting is inferior in brittle failure resistance to the TMCP and SN steels used for the diagonal columns.

The diagonal columns are welded to the cast steel blocks. The transition curves for the heat-affected zone (HAZ) and fusion line of the steel castings in the weld zone shift more toward the higher temperature side than the curve for the steel castings (Fig. 9).

To clarify the effect of low Charpy absorption energy of steel castings and weld zone on the dynamic behavior of the joint, static tensile test of full-size diagonal column joint was

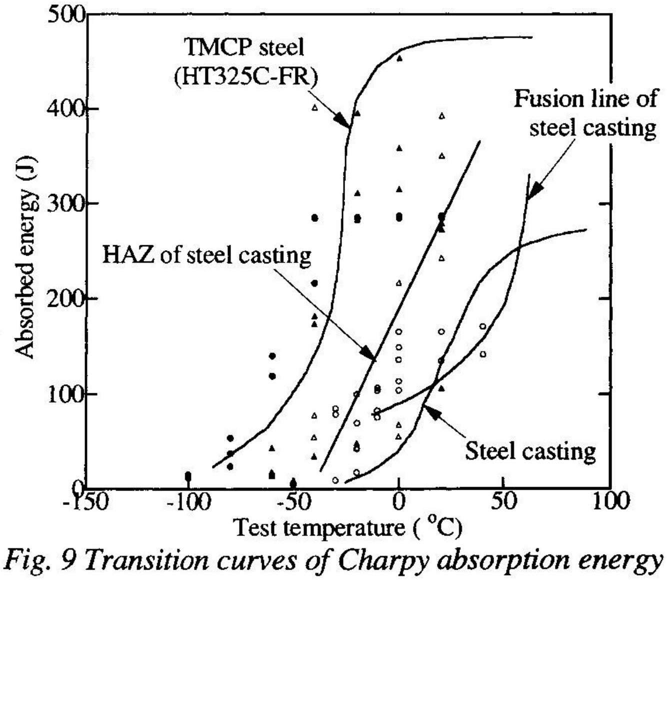

Fig. 9 Transition curves of Charpy absorption energy

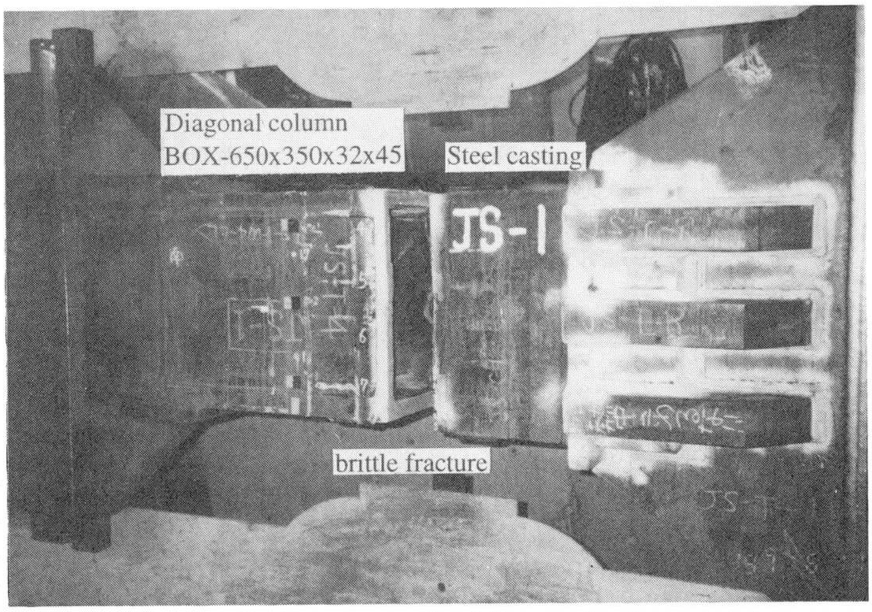

Fig. 10 Full-size test result of diagonal column joint

conducted. The primary structure of the present building is of elastic design. According to the results of the test, design is not adversely affected so long as the maximum strength is more than 1.2 times the specified yield axial force of 24,500 kN.

Three full-size test specimens of diagonal column joints were fabricated, simulating the actual diagonal column joint. Erection pieces were set to these specimens. For the locations requiring site welding, welding was carried out with the specimens inclined obliquely. Tensile test was conducted after cooling the specimens. This was because it was estimated that brittle fracture is more likely to be caused at a low strength because of weld defects if the test is conducted at a temperature at which the Charpy absorption energy becomes very low. The cooling temperature was set at -20°C for two test specimens and at -50°C for one specimen.

All test specimens failed in a brittle manner (Fig. 10). The maximum strength was 1.26 ~ 1.56 times the specified yield axial force. The fracture initiated from the weld defect. This weld defect was a small defect, acceptable according to the standards of the Architectural Institute of Japan.

Based on the results described above, it is estimated that the design of the present building is not adversely affected by the performance of steel castings and weld zone.

5. CONCLUSION

To realize seismic design for a high-rise building using diagonal lattice tubes, the building was designed on the assumption that it consisted of a primary structure and seismic dampers.

Acknowledgment

This building was designed by Plantec Architects. We wish to express our appreciation to this office for its kind cooperation in our study.

The full-size joint test was supervised by Professor Koji Morita of Chiba University. We wish to thank him for his valuable guidance and advice.

References

Connor, J. J., Wada, A., Iwata, M., and Huang, Y. H. (1997) "Damage-controlled Structures. I: Preliminary design methodology for seismically active regions.", *Journal of structural engineering*, April, 423-431

Fujimoto, M., Wada, A., Iwata, M., and Nakatani, F. (1975). "Nonlinear three dimensional analysis of steel frame structure.", *Transactions of A.I.J.*, 227, 75-90

Maeda, Y., Nakata, Y., Iwata, M., and Wada, A. (1998). "Fatigue of axial-yield type hysteresis dampers.", *Transactions of A.I.J.*, 503, 109-115

Nakamura, Y., Ono, T., Iwata, M., and Kako, Y. (1997). "The influence of notch, temperature and strain rate on the mechanical properties of steels.", *Summaries of technical papers of annual meeting A.I.J.*, 497-500

Ono, T., Kaminogo, T., Yoshida, F., Iwata, M., and Hayashi, K. (1997) " A study on material properties and hysteretic behavior of metallic material.", *Transactions of A.I.J.*, 498, 137-143