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# NEW DUCTILE STEEL FRAMES LIMITING DAMAGE TO CONNETION ELEMENTS AT THE BOTTOM FLANGE OF BEAM-ENDS (PART 2.)

**Shoichi KISHIKI[1], Satoshi YAMADA[2], Toru TAKEUCHI[3], Kazuaki SUZUKI[4], Akira WADA[5]**

## SUMMARY

In the Northridge (1994) and Kobe (1995) Earthquakes, some buildings lost structural functions, although many buildings avoided collapse so as to save human life. The loss of the structural function caused the stop of social and industrial activities, and severe economic loss. About steel structures, some buildings suffered damage at beam-column connections. A feature of the damage was fracture of bottom flanges. After the disaster, a remarkable number of studies have been made on beam-to-column connections. Some of them tried to investigate the cause of the fracture, and others proposed new connection details to resolve the issues. Nevertheless, in these studies, little attention has been paid to repairing the damage part caused by an earthquake.

The purpose of this study is to propose new ductile steel frames, which realize not only structural performances but also easy repair after an earthquake. In this system, plastic deformations concentrate in the exchangeable connection elements (the weak-web-split-tee) at the bottom flange of beam-ends. In this paper, two series of quasi-static tests were carried out. First series are axial loading test of the weak-web-split-tee, and second series are tests of beams with the weak-web-split-tee. From the result of these tests, we verified that this system had efficient deformation capacity, and easy repair.

[1] Graduate Student, Structural Engineering Research Center, Tokyo Institute of Technology, Japan. e-mail: kishiki@serc.titech.ac.jp
[2] Associate Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan. e-mail: naniwa@serc.titec.ac.jp
[3] Associate Professor, Dept. of Architecture and Building Engineering, Tokyo Institute of Technology, Japan. e-mail: ttoru@arch.titech.ac.jp
[4] Project Manager, Building Construction Division, Nippon Steel Corporation, Japan. e-mail: suzuki.kazuaki@eng.nsc.co.jp
[5] Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan. e-mail: wada@serc.titech.ac.jp

## INTRODUCTION

In the Northridge (1994) and Kobe (1995) Earthquakes, some buildings suffered damage and lost structural functions, although many buildings avoided collapse so as to save human life. If a heavy earthquake occurs in urban areas, the loss of the function of urban facilities would cause severe economic loss. In urban areas, social and industrial activities cannot be lost for long. Therefore, it is very important for a structural engineer to consider restoring buildings soon after an earthquake. One of the methods that give buildings this ability is the Damage-Controlled-Structure (Wada et al., 1992 and Y. H. Huang, 1995) and it is shown in Fig.1. This system consists of a mainframe and dampers. The mainframe only supports gravity and can remain in elastic range during an earthquake, because dampers absorb the input energy of the earthquake. Therefore, buildings can be used continuously by repairing and exchanging dampers. Today, many high-rise buildings based on the design method of the Damage-Controlled-Structure are being constructed.

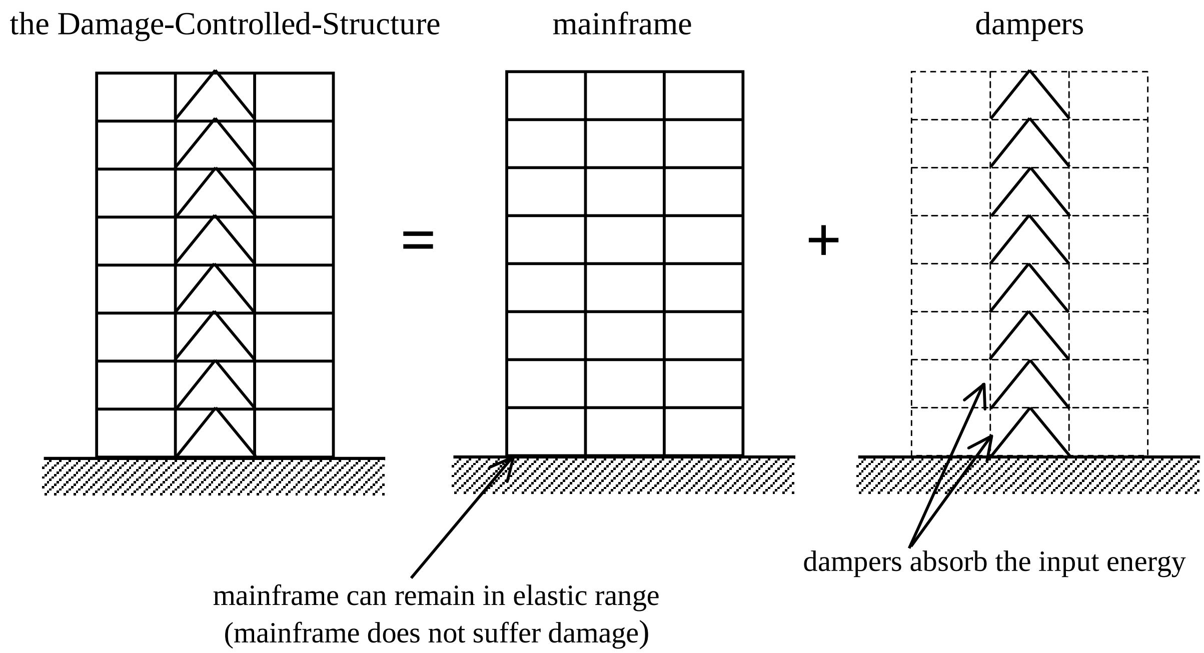


Fig.1 the Damage-Controlled-Structure (Wada et al., 1992 and Y. H. Huang, 1995)

However, in urban areas, there are many low-rise or medium-rise buildings which are not suitable for applying dampers. In the case of these buildings, naturally, energy absorption of an earthquake must be expected at the beam-ends (shown in Fig.2 (a)). And even if there were low-rise or medium-rise buildings with dampers, high rotation capacities would be required at the beam-ends of a mainframe (shown in Fig.2 (b)). It means that most low-rise or medium-rise buildings had been built based on the seismic design permitting damage at the beam-ends.

In the two earthquakes mentioned above, many steel structures suffered damage at beam-to-column connections, and some fractures of bottom flanges occurred at beam-to-column connections. After these earthquakes, a remarkable number of studies have been made on beam-to-column connection. Some of them tried to investigate the causes of these fractures, and others proposed the new connection details to resolve the issues. Examples of the proposed details are as follows: the reduced beam section detail (RBS), the horizontal-haunch beam detail, the no-weld access hole detail, and the improved weld access hole detail. And many test results have showed us that each of them prevents a premature fracture and has a large plastic rotation capacity. As the result, the RBS detail has been recommended in the U.S. and no-weld access hole detail has been adopted in Japan. Nevertheless, seismic design with these details is based on the plastic rotation capacity of main members in the mainframe. And in those studies, little attention has been paid to repairing the damage part. Consequently, it is hard to restore these buildings soon when using these details. In other words, these proposed details have not been able to solve the issues that the past disasters caused.

If it is easy to repair the mainframe with or without dampers, the buildings can be restored soon after an earthquake. It is possible to do it even if they are naturally low-rise or medium-rise buildings. The purpose of this study is to propose new ductile steel structures, which realize not only structural performance but also easy repair after a heavy earthquake. Main feature of this system is that plastic deformation concentrates on connection elements (the weak-web-split-tee, see 2.2.) at the bottom flange of beam-ends in the mainframe. In this paper, two series of quasi-static tests were carried out. From these tests, we verified that this proposed system realize.

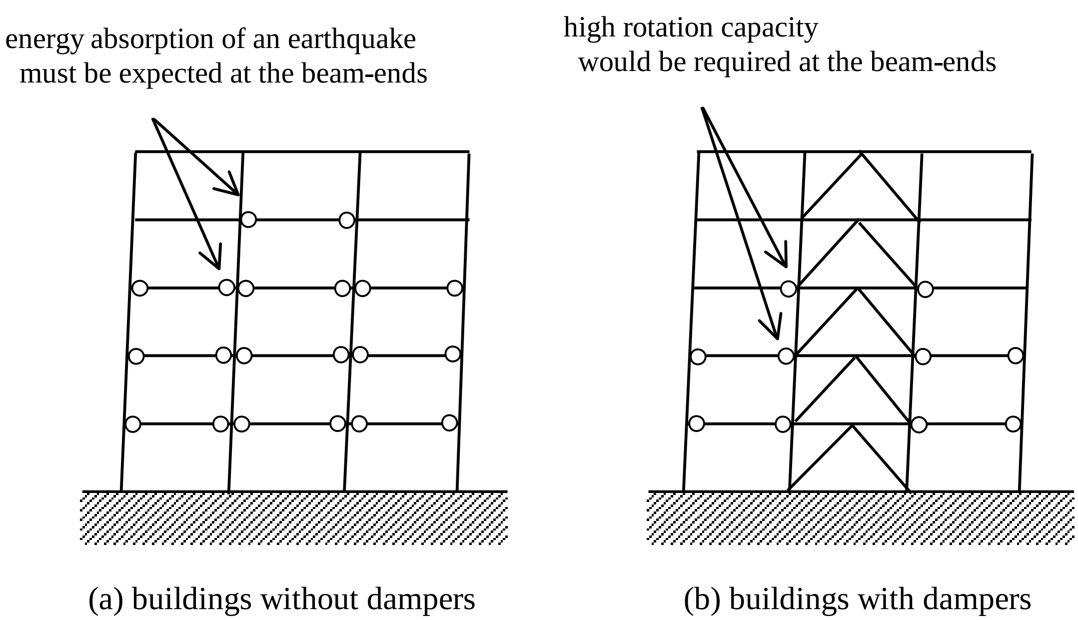


Fig.2 a seismic design based on damage at the beam-ends (low-rise or medium-rise buildings)

## PROPOSAL OF NEW DUCTILE STEEL FRAMES

**New ductile steel frames**

There are two conditions that must be met to make structures easily repairable. One of them is to constitute structures using exchangeable members. The other is to limit damage to some of these exchangeable elements. In the Damage-Controlled-Structure, dampers on which damage concentrates are connected to a mainframe by exchangeable high-strength bolts. Naturally, beams and columns of the mainframe that are connected by high-strength bolts are more easily repairable than those that are welded. And it is thought that, by designing connection elements (Split-Tee (T-stub) or Angle) that are weaker than the beam and column, it is possible to limit damage to them. However, conventional Split-Tee (T-stub) shows different behaviors in tension and compression. This characteristic behavior prevents limiting damage to exchangeable elements. A behavior of a frame with conventional Split-Tee is shown in Fig.3. In the state of this deformation, a compression force occurs on the beam because the rotation points of left and right side differ. Consequently, at the connection, stiffness and yield strength would increase with this compression force, and local buckling on the bottom flange might be caused by this compression force. It means that the state of the deformation with conventional Split-Tee is not suitable for limiting damage to connection elements.

With regards to limiting damage, the desirable state of the deformation with bolted connections would be shown in Fig.4. Main feature of this behavior is that plastic deformation is limited to the connection elements at the bottom flange. Consequently, The rotation points of left and right side stay at the top flange. Naturally, it avoids damage to the connection elements at the top flange, which is difficult to exchange. The point we wish to emphasize is that we can concentrate deformations of a mainframe on Split-Tee at the bottom flange, if the connection elements show the same behaviors in tension and compression. By repairing and exchanging the connection elements at the bottom flange after an earthquake, buildings can continue to be used. Consequently, even if the building is not suitable for applying dampers or cannot absorb the input energy with only dampers, it can be repaired easily, such as the Damage-Controlled-Structure.

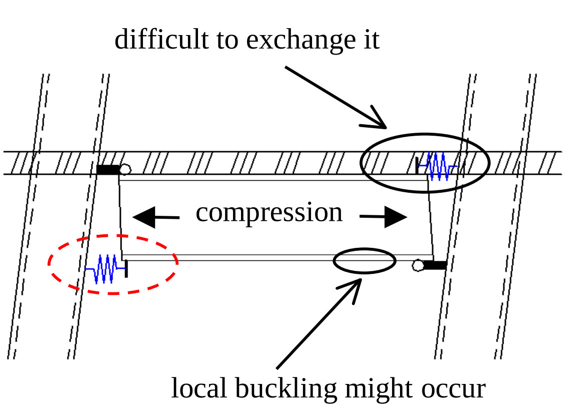


Fig. 3 The conventional deformation
(with conventional Split-Tee)

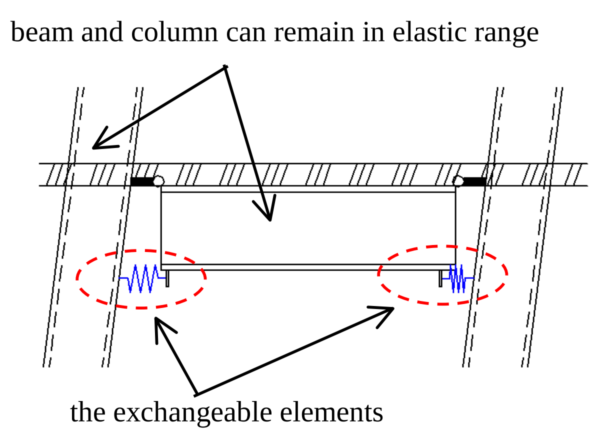


Fig. 4 The desirable deformation
(with the weak-web-split-tee)

**New connection elements (the weak-web-split-tee)**

In order to form the desirable deformation to limit damage (shown in Fig.4), the damage must concentrate on the connection elements at the bottom flange. It means that the elements have to show same behavior in tension and compression. The new connection elements (shown in Fig.5), which are proposed by us, satisfy this requirement. A feature of the connection elements is that they have a reduced section at the web plate. By designing the weak section, it allows the connection element to reach yield strength earlier than the beam, column, and the connection element at the top flange. As the result, the rotation point of beam-ends would stay at the top flange, and plastic deformations of the mainframe would concentrate on the connection elements at the bottom flange. Nevertheless, naturally, buckling occurs at the weak section when it is in compression. Therefore, we use the buckling resistance equipment shown in Fig.5. Buckling of the weak web is avoided by putting the weak web between the bottom flange of the beam and the resistance equipment. By using the buckling resistance method, the Split-Tee can show the stable deformation capacities in tension and compression (shown in Fig.5).

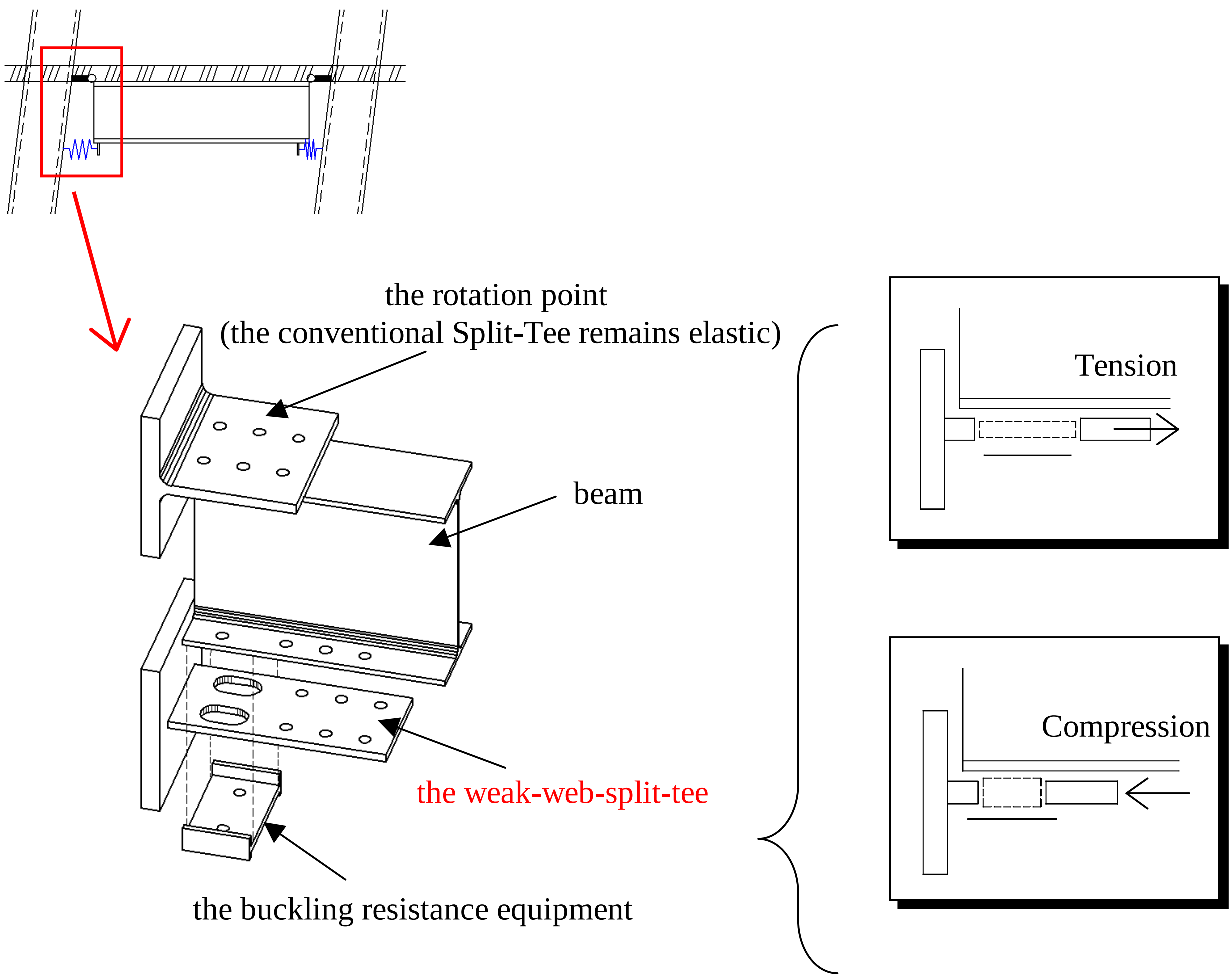


Fig. 5 The beam-to-column connection system with the weak-web-split-tee

## AXIAL LOADING TESTS OF THE CONNECTION ELEMENTS

**Specimens**

Axial loading tests of the connection element were conducted in order to verify that it is possible to realize the proposed system. Specimens were designed on the basis of half of beam-to-column connections in low-rise or medium-rise buildings. In design, the beam section was assumed to be H-300x150x6.5x9 (SS400). If a rotation angle of 1/100 occurs at this connection, an axial deformation of 3mm occurs at the weak-web. Consequently, we decided the standard length (30mm) of the weak-web so that it might become the weak-web with strain of 10% or loss. And we decided the section area of the weak-web so that the maximum strength of it might become less than yield strength of beam flange sections. A detail of the specimen is shown in Fig.6. Specimens were made by welding plate of 12mm and 28mm, and the steel grade of them was SS400. A list of mechanical properties is given in Table 1. Testing parameters for specimens were as follows: (1) length of the weak-web (Lp=30mm, 45mm), (2) with or without the buckling resistance equipment. Length of the weak-web is shown in Fig.6, and the buckling resistance equipment is shown in Fig.5 and Fig.6. And loading history is given in Fig.7. The number of specimens was 4, and a list of them is shown in Table 2.

**Test procedure**

The test setup is shown in Fig.8. The specimen was installed between frame and actuator. The axial load and deformation of the specimen were measured during the test. Displacement transducers were placed on both sides of a specimen (shown in Fig.8). Displacements were measured from flange to first high-strength bolts of friction connection.

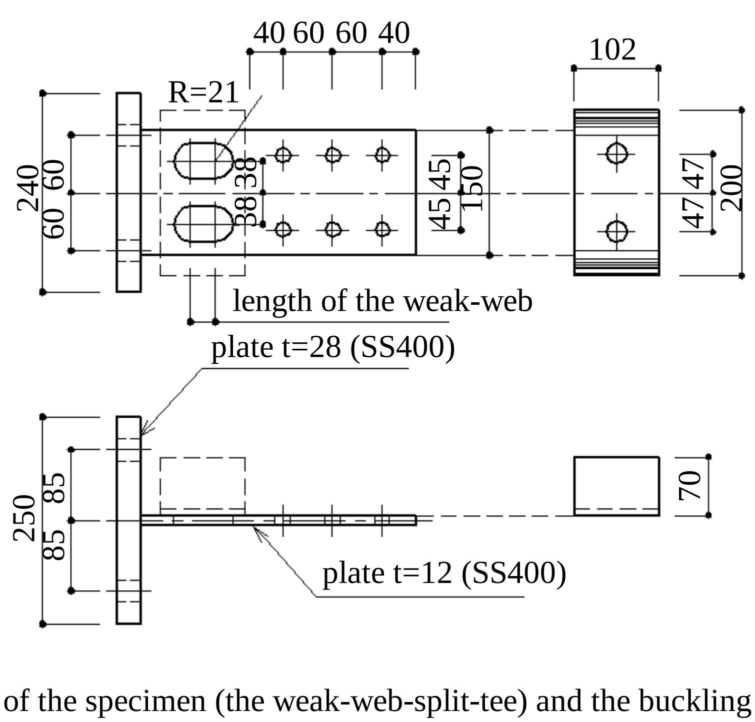


Fig. 6 A detail of the specimen (the weak-web-split-tee) and the buckling resistance equipment

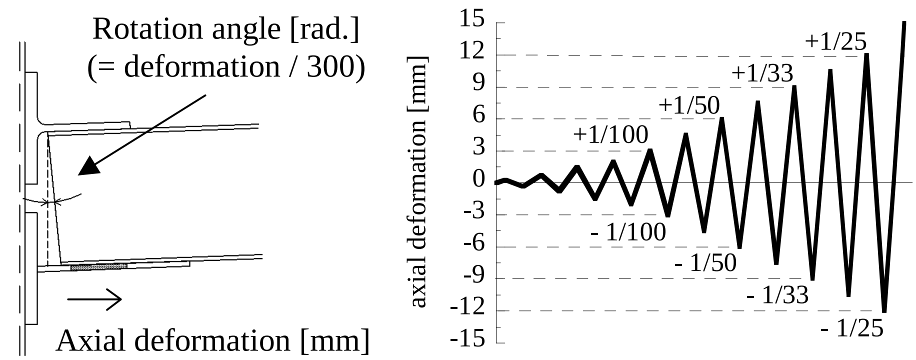


Fig. 7 Rotation angles of beam-end and Loading history

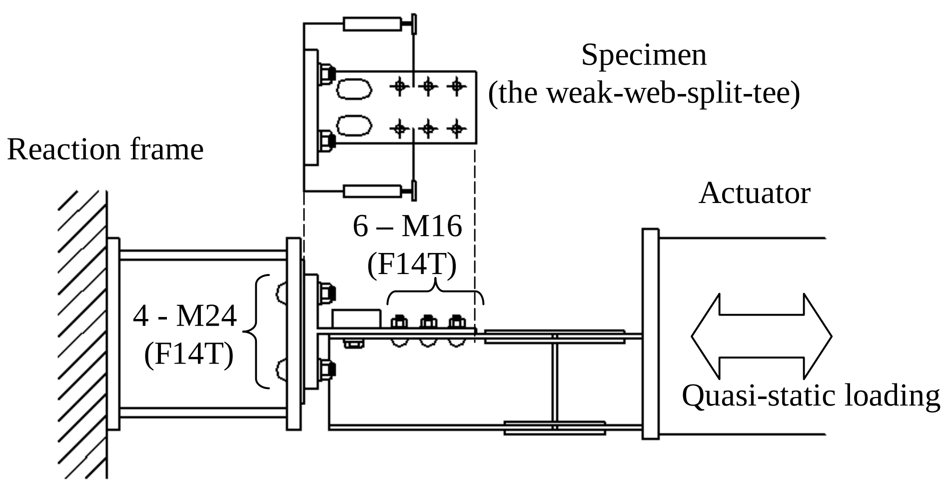


Fig. 8 Test set-up (axial loading test of the weak-web-split-tee)

Table 1 List of mechanical properties

| | grade | thickness [mm] | yield point [N/mm$^2$] | maximum stress [N/mm$^2$] | Y.R. [%] | elongation [%] |
|---|---|---|---|---|---|---|
| Web | SS400 | 12 | 294 | 419 | 70 | 47 |
| Flange | SS400 | 28 | 249 | 424 | 59 | 35 |

Table 2 List of specimens and testing parameters

| | specimen name | length of the weak-web $L_p$ [mm] | the buckling resistance equipment |
|---|---|---|---|
| 1 | W-30C | 30 | × |
| 2 | W-45C | 45 | × |
| 3 | WR-30C | 30 | ○ |
| 4 | WR-45C | 45 | ○ |

**Test result and consideration**

Axial load-deformation curves obtained from the tests are shown in Fig.9. In addition to this horizontal axis below, the rotation angles of beam-end (depth=300mm) corresponding to deformation are shown. In specimens without the buckling resistance equipment (W-30C, W-45C), out-of-plane buckling occurred at the weak-web when the rotation angle reached about 1/100. after out-of-plane buckling occurred, these specimens could deform until about a rotation angle of 1/25. Failure mode of these specimens was rupture at the weak-web. In specimens with the buckling resistance equipment (WR-30C, WR-45C), these specimens showed stable hysteresis curves until the weak-web ruptured. In specimen WR-45C, shown in Fig.8, in plane buckling occurred just before rupture occurred at the weak-web. A reason that the in-plane buckling occurred was that the resistance equipment was channel.

The maximum deformation of specimens with the buckling resistance equipment was smaller than that of specimens without the buckling resistance equipment. It was because strain of the weak-web reduced by out-of-plane buckling. To the contrary, in specimens with the buckling resistance equipment, strain of the weak-web increased with deformation. The relationship between absorbed energy and accumulative deformation obtained from these axial load-deformation curves is shown in Fig.10. In the figure, behavior was expressed with the solid line until strength fell to 90% of the maximum strength. The total of absorbed energy and accumulative deformation of specimens with the buckling resistance equipment were smaller than that of specimens without the buckling resistance equipment. However, when it paid attention to behavior until strength fell to 90% of the maximum strength, specimens with the buckling resistance equipment were more efficient than that specimen without that. Consequently, when applying the weak-web-split-tee to the proposed system, showing stable hysteresis curve is effective even if it was in compression.

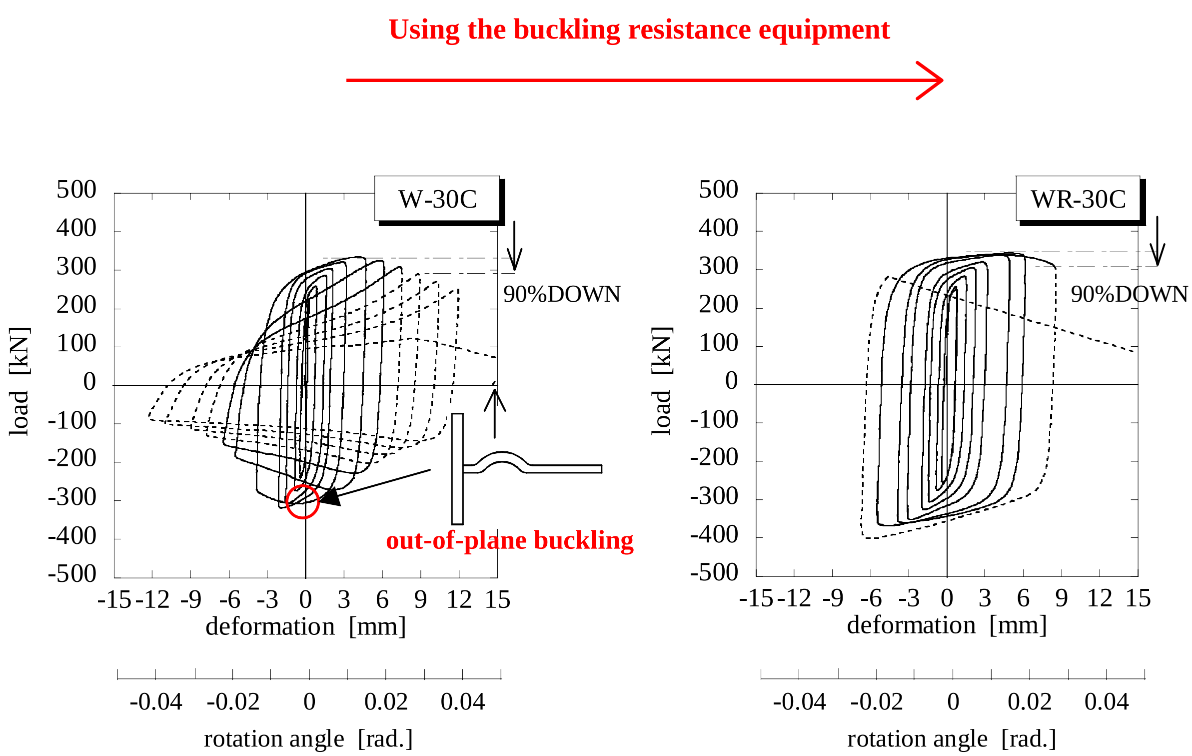


Fig. 9 (1) Axial load-deformation curves

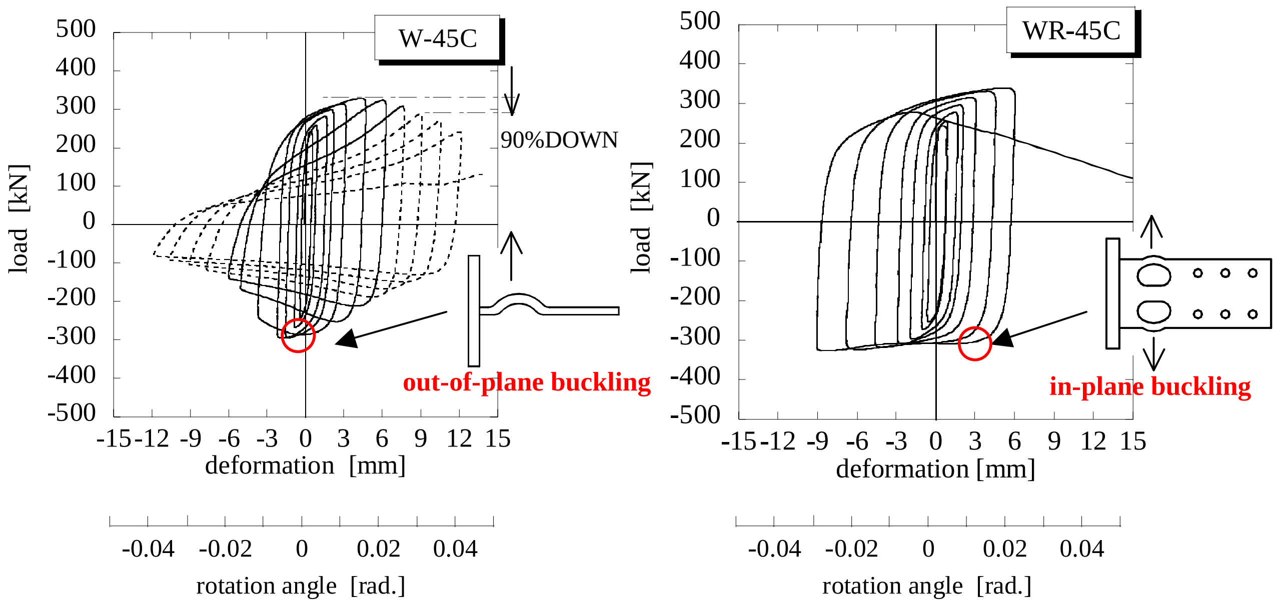


Fig. 9 (2) Axial load-deformation curves

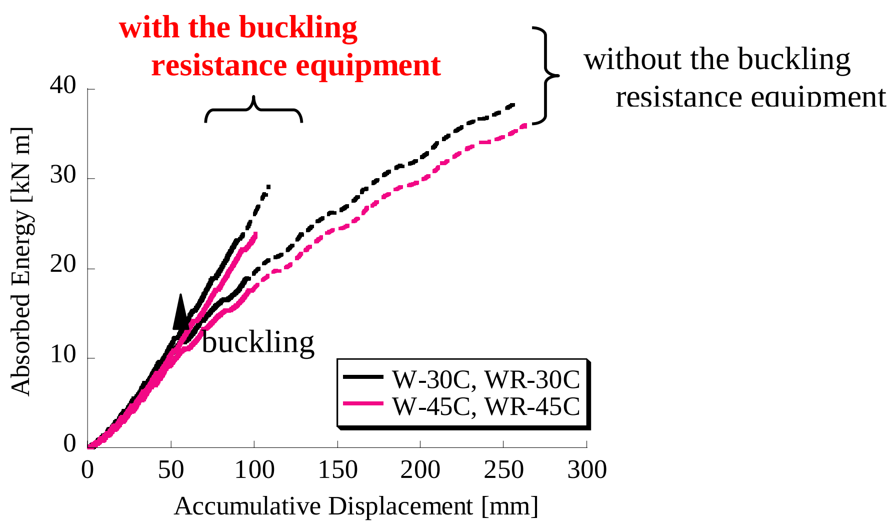


Fig. 10 Relationship between Absorbed energy and Accumulative deformation

## BENDING TESTS OF BEAM WITH THE WEAK-WEB-SPLIT-TEE

### Specimens

Bending tests were carried out to verify that beams showed a large rotation capacity, even if plastic deformation concentrated on the weak-web-split-tee. Specimens were designed on the basis of low-rise or medium-rise buildings, and had the weak-web-split-tee at the bottom flange of beam-end. The weak-web-split-tee was designed like specimen (WR-30C) of the tests of the connection elements. The difference from the specimen (WR-30C) was to use the low-yield-point steel (LYP225) at the weak-web. A connection element at the top flange of beam-end was the conventional split-tee, having no weak-web. However the connection element was designed to remain in elastic range and to be the rotation points of beam-end, until the weak-web-split-tee showed plastic deformation. A H-shaped beam was H-300x150x6.5x9 (SS400), which was the same as the assumed section in the tests of the connection elements. And column was Box-250x250x12 (STKR490), RH-250x250x9x14 (SM490A). A detail of the specimens is shown in Fig.11, and a list of mechanical properties is given in Table 3. The buckling resistance equipment was improved to H-shaped section, because in-plane buckling of the weak-web occurred in tests of the connection elements. The new buckling resistance equipment is shown in Fig.13.

**Test procedure**

The test setup is shown in Fig.12. The both end of the column of the specimen was supported with pin connections. An oil jack (500[kN]) was connected to the free end of the beam. Quasi-static cyclic loading test was carried out. During cyclic loading, a lateral displacement was supported at the point of the dashed line in Fig.12.

A lateral displacement at the free end of the beam was measured in order to be a deformation of the specimen. In other words, when the lateral deformation was measured, deformations of panel and column of the specimen were removed. A loading history was based on the lateral deformation. And the loading history is shown in Fig.14. Shear force was measured by load cell. Displacement transducers were placed on the connection elements at the top-and-bottom flange, and measured axial deformations of them.

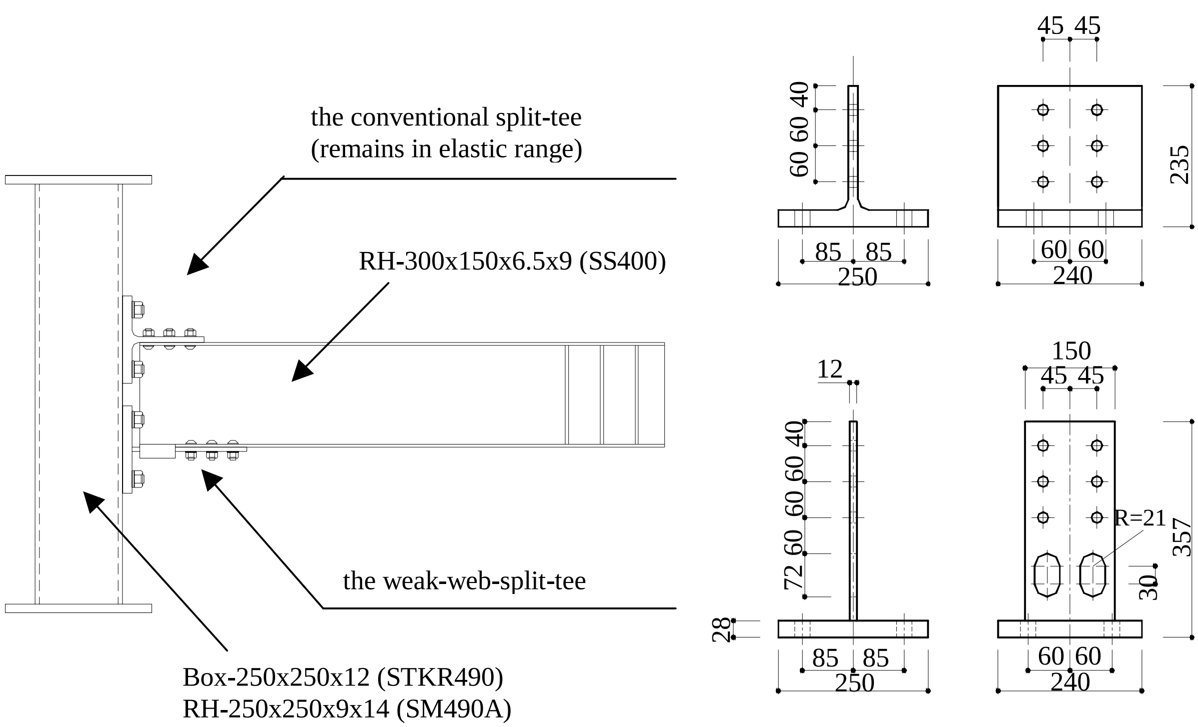


Fig. 11 Detail of the specimens

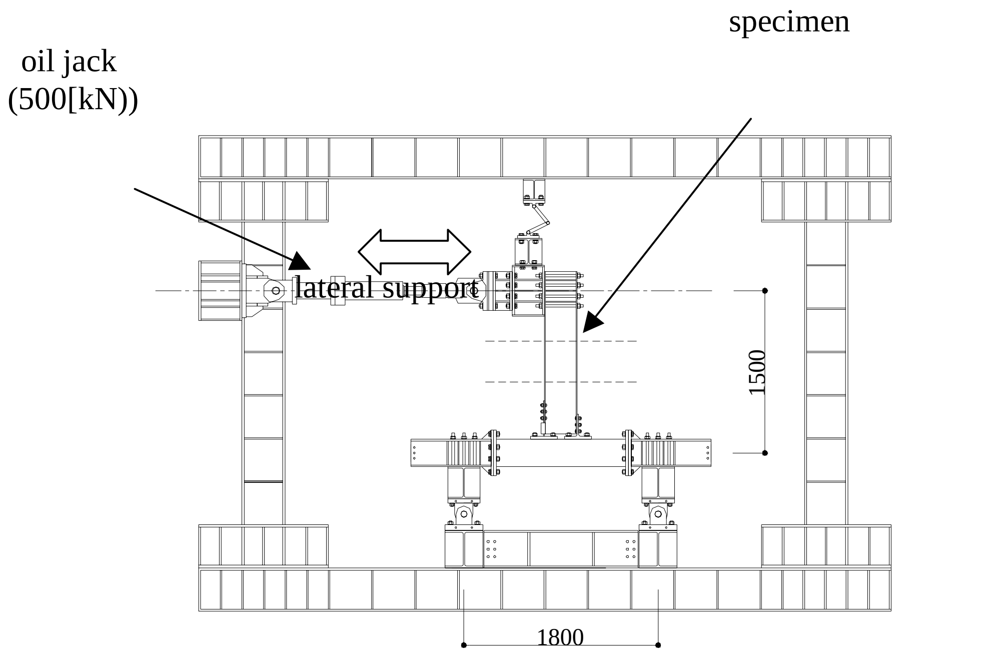

Fig. 12 Test set-up (bending test of beams with the weak-web-split-tee)

Table. 3 List of mechanical properties

| | | grade & thickness [mm] | yield point [N/mm$^2$] | maximum stress [N/mm$^2$] | yield ratio [%] | elongation [%] |
|---|---|---|---|---|---|---|
| the weak-web-split-tee | Web | LYP225 ( t = 12 ) | 237 | 300 | 70 | 37 |
| | Flange | SS400 ( t = 28 ) | 253 | 412 | 61 | 36 |
| the conventional split-tee | Web | SM490A ( t = 16 ) | 428 | 544 | 79 | 26 |
| | Flange | SM490A ( t = 28 ) | 329 | 504 | 65 | 32 |
| H-shaped Beam | Web | SS400 ( t = 6.5 ) | 375 | 494 | 76 | 26 |
| | Flange | SS400 ( t = 9 ) | 334 | 475 | 70 | 31 |
| Box Column | | STKR490 ( t = 12 ) | 480 | 533 | 90 | 21 |

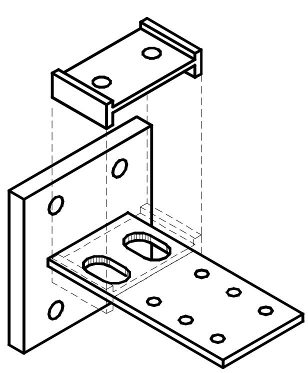
Fig. 13 The buckling resistance equipment (improved to be H-shaped section)

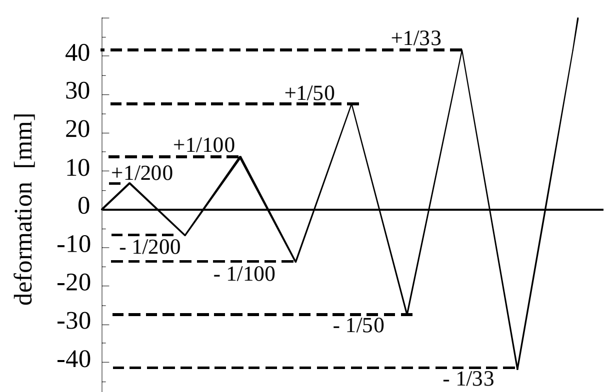

Fig. 14 Loading history

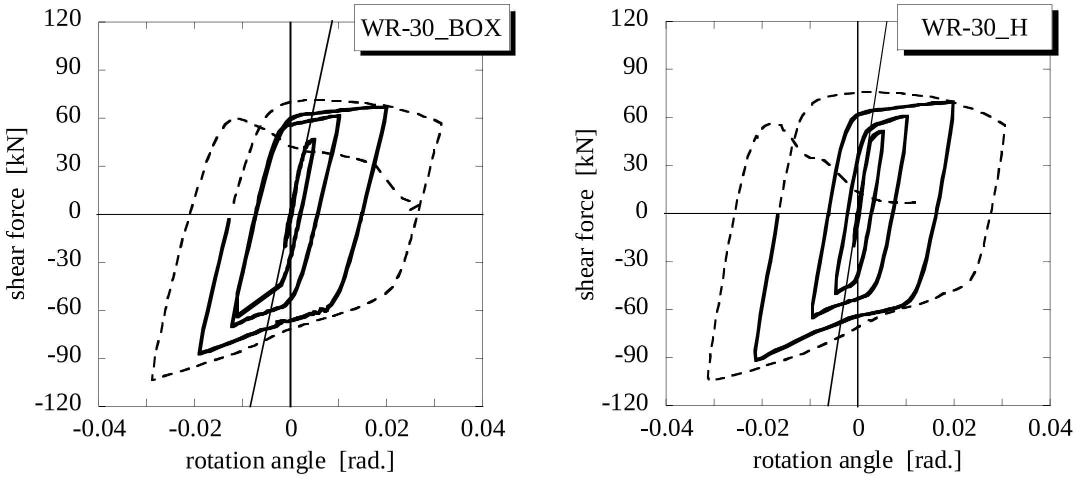


Fig. 15 Shear force-rotation angle curves

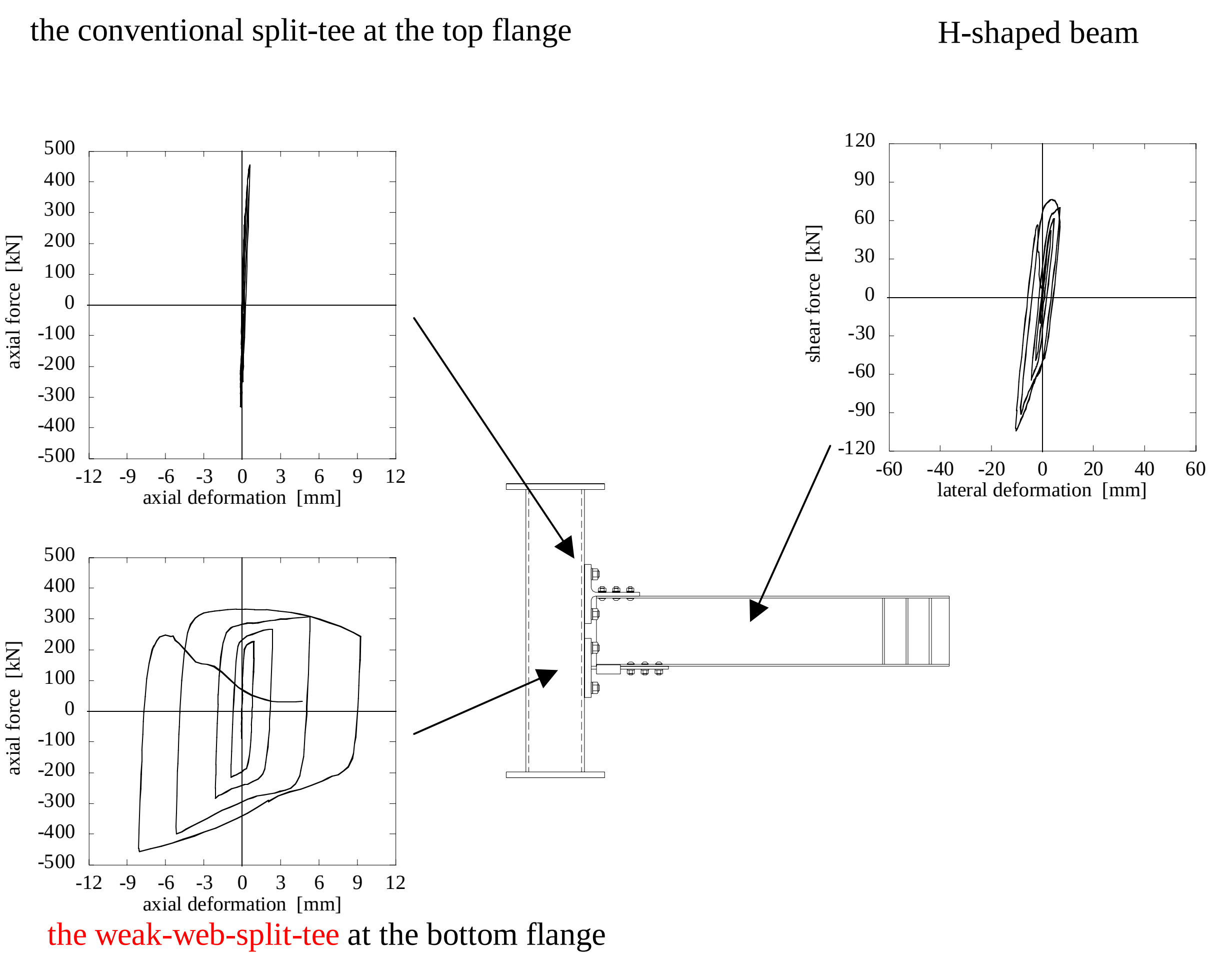


Fig. 16 Each behavior of the element that constitutes the specimen (WR-30_H)

**Test result and consideration**

Shear force-rotation angle curves obtained from the tests are shown in Fig.15. In the figure, behaviors were expressed with the solid line during rotation angle 1/50. Specimens showed stable hysteretic curve. And failure mode of the specimen was rupture at the weak-web. Shear force of the weak-web-split-tee in compression is larger than that of the weak-web-split-tee in tension. It was caused by not only increase in section area but also contact of the weak-web and the buckling resistance equipment. Both specimens showed same behavior, although type of column differed.

Each behavior of the element that constitutes the specimen is shown in Fig.16. The figures show that the conventional split-tee at the top flange and H-shaped beams remained in elastic range. In other words, the specimen was able to limit plastic deformations (damage) to the weak-web-split-tee at the bottom flange of beam-end. And it means that the specimen showed a large rotation capacity, even if plastic deformation concentrated on the weak-web-split-tee. In addition, it was easy to exchange the damage part (the weak-web-split-tee) of the specimen.

## CONCLUSIONS

Many steel structures suffered damage at beam-to-column connections in the Northridge and Kobe Earthquakes. After these disasters, although a lot of researchers proposed new connection details, most of them paid attention to repairing after an earthquake.

In this paper, we proposed the new ductile steel frame, which realize not only structural performances but also easy repair after an earthquake. Furthermore, we proposed the new connection elements, the weak-web-split-tee, to realize the proposed system. By conducting quasi-static tests of the connection elements and beams with the weak-web-split-tee, the specimens showed that it was possible to realize the proposed system.

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