Special edition paper

Development of Aseismic Ceilings for Large Spaces in Upper Floors of Buildings

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Upper floors of buildings are subjected to large external forces in earthquakes, and large horizontal forces act on ceiling members. Conventional aseismic ceilings thus require many reinforcement members to handle such forces. However, installation of reinforcement members is difficult in buildings such as stations that have much equipment in the space behind the ceiling panels.

We thus developed aseismic reinforcement members that can secure larger bearing force to reduce the number of locations to which reinforcement members are installed per unit of area. Then we carried out static horizontal load tests with two types of reinforced aseismic ceilings that were developed this time. The test results proved that the developed aseismic ceilings have larger bearing force than that of conventional aseismic ceilings.

●Keywords: Aseismic ceiling, Earthquake, Large space, Static horizontal load test

1 Introduction

Starting with the Geiyo Earthquake in 2001, at every large earthquake such as the 2003 Tokachioki Earthquake, 2005 Miyagiken-oki Earthquake and 2011 Tohoku Earthquake, gymnasiums and other buildings with large spaces suffered damage where the ceilings collapsed. In the light of that, aseismic improvement of ceilings is demanded to secure safety for users of buildings such as stations in earthquakes[1), 2)].

In aseismic improvement of ceilings, the following two points are particularly important. One is to enhance rigidity of ceilings and thus inhibit shake of ceilings by installing aseismic reinforcement members such as oblique swing controllers (braces) in the ceiling space. Another is to keep clearance to prevent impact between ceiling panels and walls.

Buildings that have large spaces, high upper floors and large ceiling space tend to receive larger horizontal force in an earthquake. They thus need many reinforcement members, resulting in increase of construction cost and time. It is also sometimes difficult to install reinforcement members to buildings with much equipment such as piping behind the ceiling panels. We therefore conceived and produced aseismic reinforcement members that can secure larger bearing force to reduce the number of locations to which reinforcement members are installed per unit of area and examined structural performance through experiments.

2 Development of Aseismic Reinforcement Members

Fig. 1 shows an overview of a conventional aseismic ceiling. The upper part of the brace is connected to a hanger bolt with fittings and the lower part is secured to a ceiling joist support with screws. As shown in Fig. 2, static horizontal load test results of the conventional aseismic ceiling demonstrate that fittings at the upper part of the brace buckled and deformed and the ceiling joist support at the lower part also buckled. The brace thus reached its ultimate state as a ceiling structure before being broken. That means performance of the brace was not fully utilized.

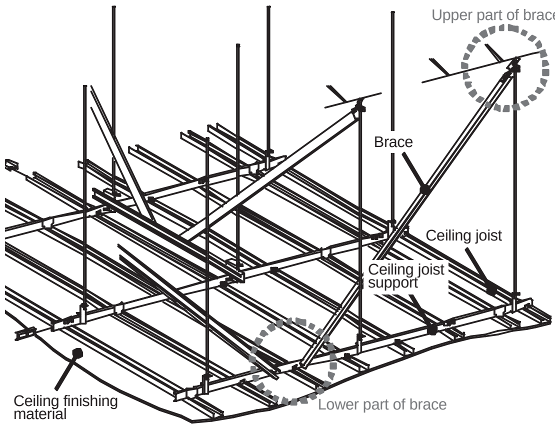
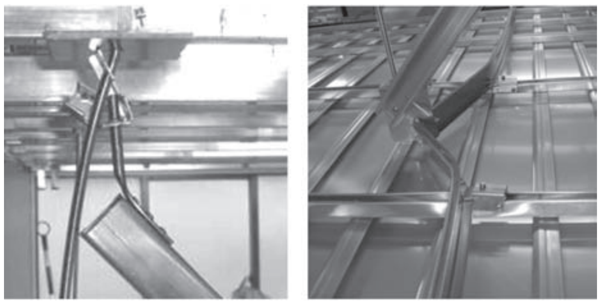


Fig. 1 Conventional Aseismic Ceiling



(a) Upper part of brace (b) Lower part of brace

Fig. 2 Destruction of Conventional Aseismic Ceiling

Based on those results, we thought that changing connections of the upper and lower parts of the brace to fittings of higher strength would improve the aseismic performance of the conventional ceiling as a whole, and we thus conceived a new fitting. The target bearing force in development was roughly twice as large as that of conventional fittings. Fig. 3 shows the developed fittings.

Development A is a fitting that connects the upper part of the brace to the hanger bolt. By adopting enclosed-type fitting to fully cover the hanger bolt, the degree of securing was improved.

Development B is a joint that connects the lower part of the brace to the ceiling joist. It consists of a steel angle connected to

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the ceiling joist and a steel cross to which the brace is connected. Adopting a steel cross enabled the brace only to be installed at one point in the direction of either the ceiling joist or the ceiling joist support.

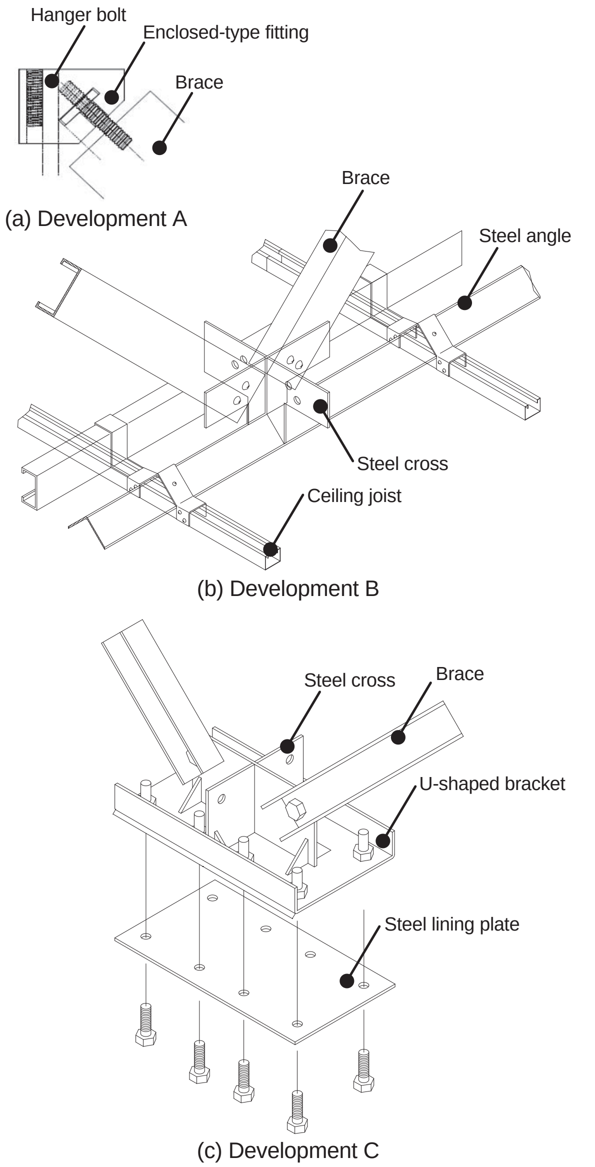


Fig. 3 Developed Aseismic Reinforcement Members

Development C is a joint that connects the lower part of the brace and the ceiling finishing material. The ceiling finishing material is held between a U-shaped bracket secured on the rear side of the ceiling and lining steel used on the finish side (t = 3.2), and it is secured with eight M10 bolts. This method has an advantage in terms of installation whereby the brace can be secured while avoiding pipes and other equipment in the ceiling space because the brace placement is not dependent on the location of the ceiling furring material. The U-shaped bracket has a cross steel, so it also enables installation of the brace in either the direction of the ceiling joist or the ceiling joist support as with development B.

Developments A, B and C all can be added to an existing ceiling later. They can thus be installed not only to new aseismic ceilings, but also to existing ceilings at aseismic improvement of the ceilings.

In introducing the developed products to aseismic ceilings, we envisaged the following two methods according to the method of securing to the ceiling structure.

1) Securing to the ceiling furring material
  - The upper part of the brace is secured to the hanger bolt with development A.
  - The lower part of the brace is secured to the ceiling joist with development B.

2) Securing to the ceiling finishing material
  - The upper part of the brace is secured directly to the building frame.
  - The lower part of the brace is secured to the ceiling finishing material with development C.

Fig. 4 shows use of the developed products for an aseismic ceiling.

Development C can be applied to aluminum spandrel and other metallic ceiling finishing material too, while the figure shows an example of its use where the ceiling is finished with a plaster board sub-ceiling and rock wool acoustic panels.

3 Strength Check Tests of Developed Products

To check the strength of the aseismic ceiling with the developed products, we carried out static horizontal load tests.

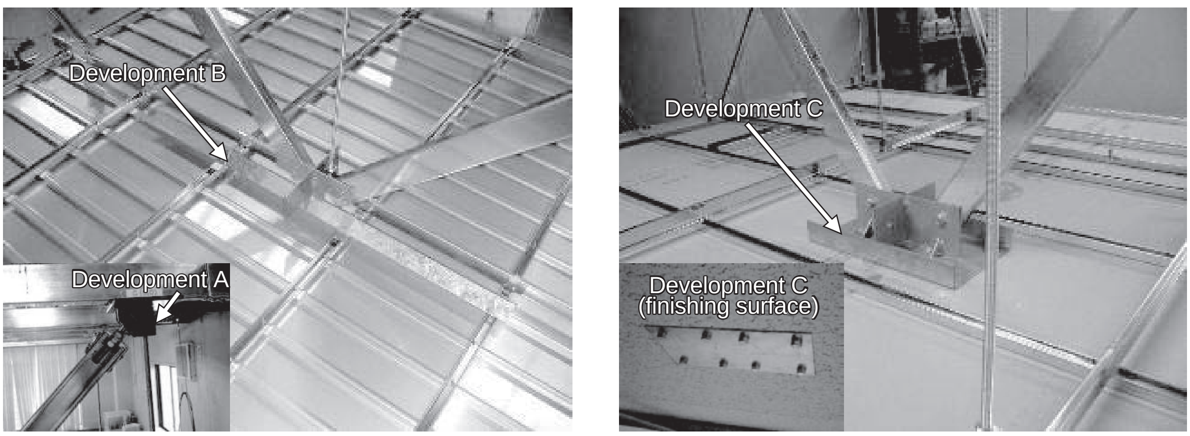


Fig. 4 Use of Developed Products

3.1 Aseismic Ceiling with Development A and B (Test 1)

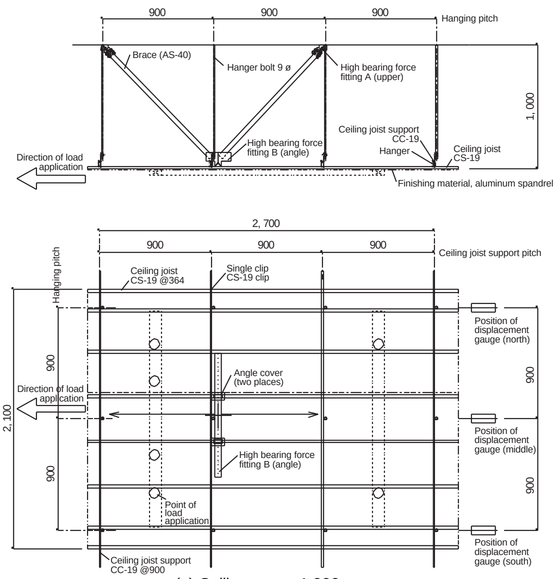
3.1.1 Test Overview

The specimen is a 2,100 mm × 2,700 mm part of an actual ceiling with steel ceiling furring. The fitting of the upper part of the brace is development A, and the fitting of the lower part is development B. The ceiling finishing material is aluminum spandrel of a working width of 105 mm (t = 0.8 mm) secured with 3 mm screws. With the C-shaped steel connected to a hydraulic cylinder, load was uniformly applied to six points on the aluminum spandrel. The load application level was measured with a load cell and the displacement with a displacement gauge.

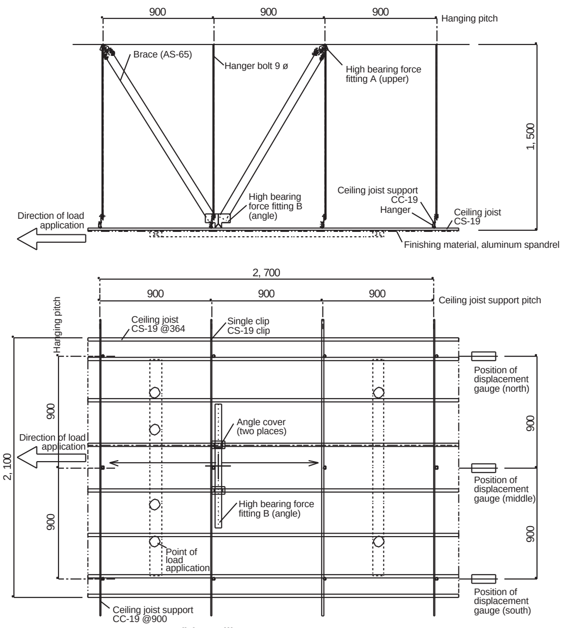
The test parameters are the ceiling space (1,000 mm, 1,500 mm or 2,000 mm) and the direction of load application (direction of ceiling joist or ceiling joist support). Fig. 5 shows an example schematic of the load application test in the ceiling joist direction. Table 1 is the list of the specimens.

3.1.2 Test Results

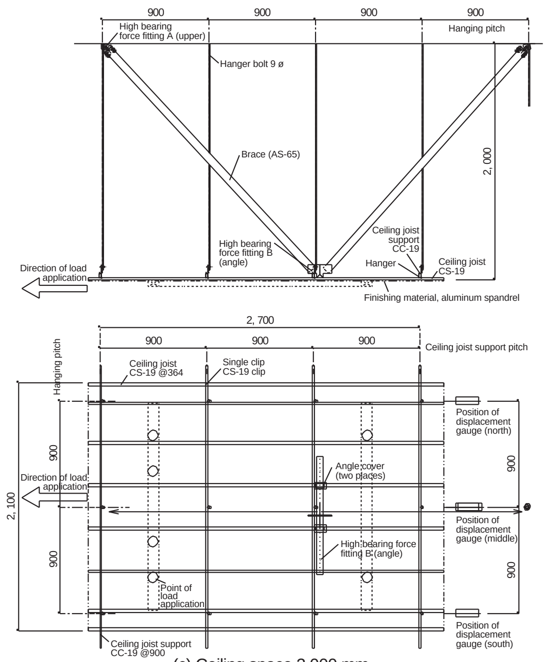
Fig. 6 shows the relationship between load and displacement in each test. The ultimate state of individual specimens is as follows.



(a) Ceiling space 1,000 mm



(b) Ceiling space 1,500 mm



(c) Ceiling space 2,000 mm

Fig. 5 Schematic of Specimen for Test 1 (Load Applied in Direction of Ceiling Joist)

Table 1 List of Specimens for Test 1

No.	Test No.	Specimen No.	Direction of load application	Ceiling space	Brace			Fitting for upper part of brace	Fitting for lower part of brace	Finishing material
				(mm)	Type	Angle of installation	Placement			
1	RCF1	RCF1-1	Ceiling joist	1000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
2		RCF1-2	Ceiling joist	1000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
3	RCF2	RCF2-1	Ceiling joist	1500	AS-65	60°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
4		RCF2-2	Ceiling joist	1500	AS-65	60°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
5	RCF3	RCF3-1	Ceiling joist	2000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
6		RCF3-2	Ceiling joist	2000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
7	RCF4	RCF4-1	Ceiling joist support	1000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
8		RCF4-2	Ceiling joist support	1000	AS-40	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
9	RCF5	RCF5-1	Ceiling joist support	1500	AS-65	60°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
10		RCF5-2	Ceiling joist support	1500	AS-65	60°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
11	RCF6	RCF6-1	Ceiling joist support	2000	AS-65	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)
12		RCF6-2	Ceiling joist support	2000	AS-65	45°	V-shape	Development A	Development B	Aluminum spandrel (t = 0.8)

- RCF1-1: At 6375 N, brace on compression side buckled.
- RCF1-2: At 6762 N, brace on compression side buckled.
- RCF2-1: At 7470 N, brace on compression side buckled.
- RCF2-2: At 6947 N, steel angle of development B deformed. Lower end of brace interfered with and deformed ceiling joist support.
- RCF3-1: At 6590 N, brace on compression side buckled, deforming hanger bolt near center of brace.
- RCF3-2: At 6917 N, brace on compression side buckled, deforming hanger bolt near center of brace.
- RCF4-1: At 5865 N, ceiling joist near cover of angle steel of development B deformed, and screws secured to ceiling joist came off.
  At 6395 N, screws holding spandrel came off due to deformation of ceiling joist.
- RCF4-2: At 6577 N, screws holding spandrel came off due to ceiling joist near cover of angle steel of development B being deformed.
- RCF5-1: At 5707 N, U-shaped bracket at upper part of brace on compression side deformed, and development A rotated.
- RCF5-2: At 6902 N, development A rotated and brace on compression side twisted.
- RCF6-1: At 5300 N, ceiling joist near cover of angle steel of development B deformed, and screws secured to ceiling joist came off.
  At 6322 N, screws holding spandrel came off due to deformation of ceiling joist.
- RCF6-2: At 4500 N, ceiling joist near cover of angle steel of development B deformed, and screws secured to ceiling joist came off.
  At 6890 N, screws holding spandrel came off due to deformation of ceiling joist.

3.1.3 Consideration

Table 2 shows the maximum bearing force and the displacement at that bearing force as well as the load at deformation that is 1/100 of the ceiling space (δ1/100) in each test. For comparison, it also shows the static horizontal load test of conventional aseismic ceilings with the same conditions applied for the ceiling space and the direction of load application.

With a ceiling space of 1,000 mm, no remarkable difference is found in the maximum bearing force according to the direction of load application, but rigidity is higher in the direction of the ceiling joist support. This is because the bending deformation of the ceiling joist with relatively low bearing force (around the joint with development C) reached its ultimate state in the direction of the ceiling joist support, while in direction of the ceiling joist the buckling of the brace on the compression side reached its ultimate state. A similar tendency was also seen in 1,500 mm and 2,000 mm ceiling spaces.

For maximum bearing force, the results were mostly more than 6,000 N in each case.

When designing an aseismic ceiling, we set a certain clearance between the wall and the ceiling and decide on the number of locations to install aseismic reinforcement members so that the

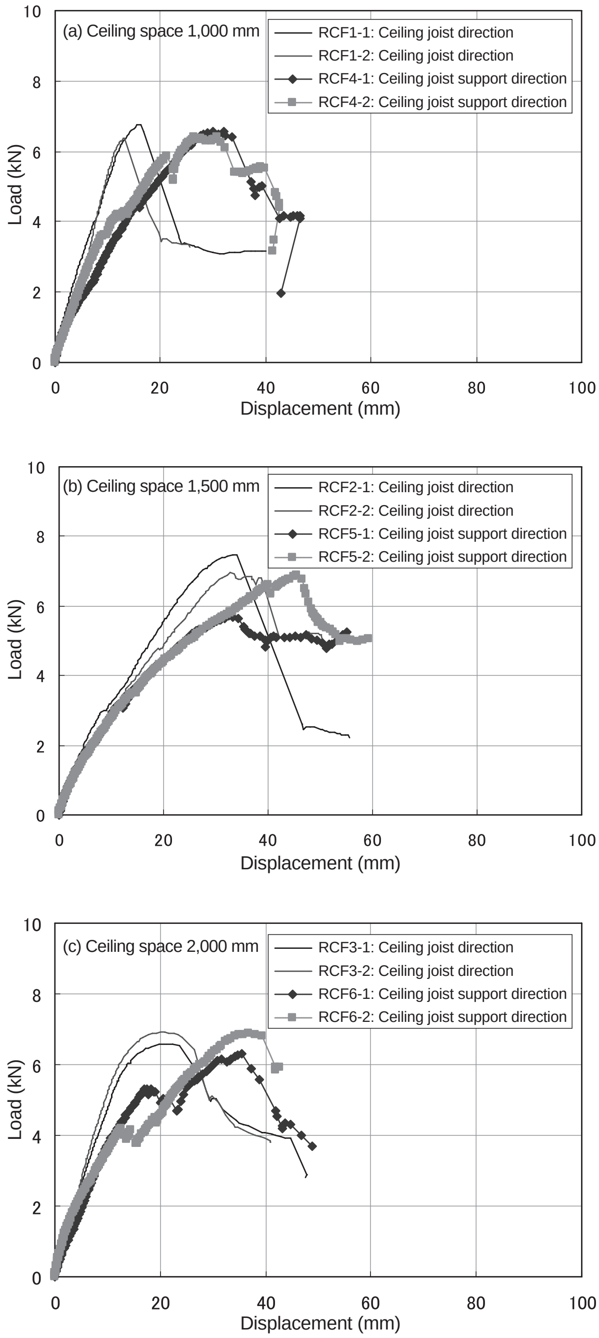


Fig. 6 Load - Displacement Relationship

Table 2 List of Test 1 Results

No.	Test No.	Specimen No.	Max. bearing force (N)	Displacement at max. bearing force (mm)	Load at δ1/100 displacement (N)	Load at δ1/100 displacement of conventional aseismic ceiling (N)
1	RCF1	RCF1-1	6,762	16.2	5220	1640
2		RCF1-2	6,375	13.2	5360	
3	RCF2	RCF2-1	7,482	33.1	4375	1820
4		RCF2-2	6,947	32.7	4002	
5	RCF3	RCF3-1	6,590	22.3	6560	1940
6		RCF3-2	6,917	20.8	6910	
7	RCF4	RCF4-1	6,577	32.1	3167	2969
8		RCF4-2	6,395	30.7	3757	
9	RCF5	RCF5-1	5,707	32.4	3690	1576
10		RCF5-2	6,918	45.5	3602	
11	RCF6	RCF6-1	6,322	35.5	4945	1678
12		RCF6-2	6,890	36.8	4570	

displacement of the surface of the ceiling according to the assumed seismic force could be absorbed within that clearance. Thus, the larger the bearing force of aseismic reinforcement members per installation point is to a given deformation, the fewer the number of points where reinforcement members are needed. When the clearance is δ1/100, the load at that deformation with an aseismic ceiling using the developed products was larger than the load at roughly twice that of a conventional aseismic ceiling. That indicates using the developed products can reduce the number of points where aseismic reinforcement members need to be installed to approx. half that of a conventional ceiling. For actual introduction, however, well-balanced placement of aseismic reinforcement members is needed according to factors such as the planar shape of the ceiling.

3.2 Aseismic Ceiling with Development C (Test 2)

3.2.1 Test Overview

The specimen is a 3 m × 3 m part of an actual ceiling with steel ceiling furring. The fitting of the lower part of the brace is development C. The upper part of the brace is secured with bolts and nuts to the L-shaped angle welded to the frame in the test laboratory. The test parameters are the direction of load application (ceiling joist or ceiling joist support direction) and the finishing material (aluminum spandrel t = 0.8 or plaster board sub-ceiling t9.5 + rock wool acoustic panels t12). The methods of load application and measurement are the same as in Test 1. Fig. 7 shows a full view of the specimen, Fig. 8 a schematic of the specimen, and Table 3 a list of the specimens.

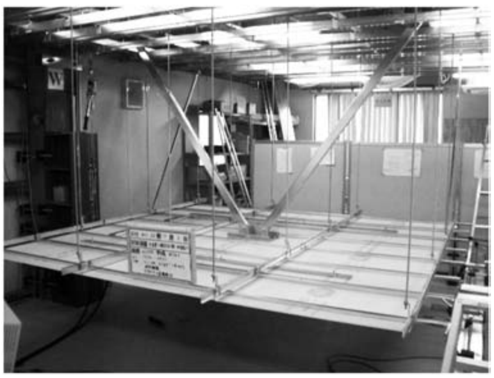


Fig. 7 Full View of Specimen

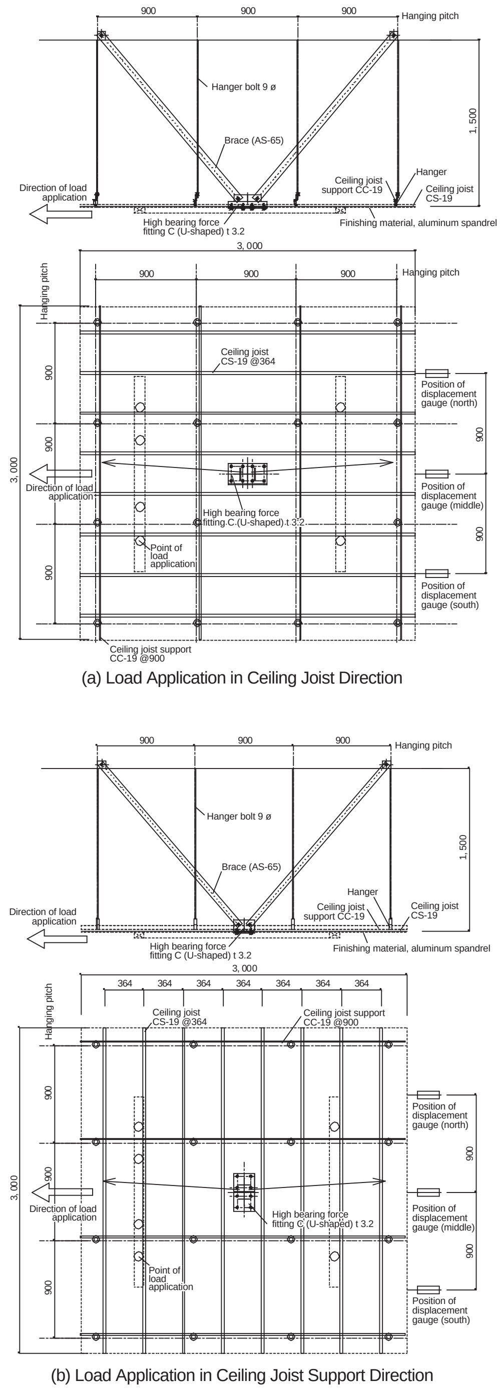


Fig. 8 Schematic of Specimen for Test 2

Table 3 List of Specimens for Test 2

No.	Test No.	Specimen No.	Direction of load application	Ceiling space (mm)	Brace Type	Brace Angle of installation	Brace Placement	Fitting for upper part of brace	Fitting for lower part of brace	Finishing material
13	RBE1	RBE1-1	Ceiling joist	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Aluminum spandrel (t = 0.8)
14		RBE1-2	Ceiling joist	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Aluminum spandrel (t = 0.8)
15	RBE2	RBE2-1	Ceiling joist	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Plaster board (t = 9.5) + rock wool acoustic panel (t = 12)
16		RBE2-2	Ceiling joist	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Plaster board (t = 9.5) + rock wool acoustic panel (t = 12)
17	RBE3	RBE3-1	Ceiling joist support	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Aluminum spandrel (t = 0.8)
18		RBE3-2	Ceiling joist support	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Aluminum spandrel (t = 0.8)
19	RBE4	RBE4-1	Ceiling joist support	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Plaster board (t = 9.5) + rock wool acoustic panel (t = 12)
20		RBE4-2	Ceiling joist support	1500	AS-65	45°	V-shape	Beam angle, secured with bolts and nuts	Development C	Plaster board (t = 9.5) + rock wool acoustic panel (t = 12)

3.2.2 Test Results

Fig. 9 shows the relationship between load and displacement in each test. The ultimate state of individual specimens is as follows.

- RBE1-1: At 3000 N, development C rotated in direction of structure plane of brace, and brace on compression side sank down.
  At 7795 N, screws that secured spandrel near development C to ceiling furring material came off.
- RBE1-2: At 4000 N, development C rotated in direction of structure plane of brace, and brace on compression side sank down.
  At 7547 N, brace on compression side buckled.
- RBE2-1: At 5152 N, head of screws came out from finishing material.
  At 7987 N: brace on compression side buckled.
- RBE2-2: At 4500 N, development C began to dig in to finishing material.
  At 7585 N, brace on compression side buckled.
- RBE3-1: At 6000 N, ceiling joist bent and deformed in direction of load application.
  At 7395 N, brace on compression side buckled.
- RBE3-2: At 7490 N, brace on compression side buckled.
- RBE4-1: At 7445 N, brace on compression side buckled.
- RBE4-2: At 7645 N, brace on compression side buckled.

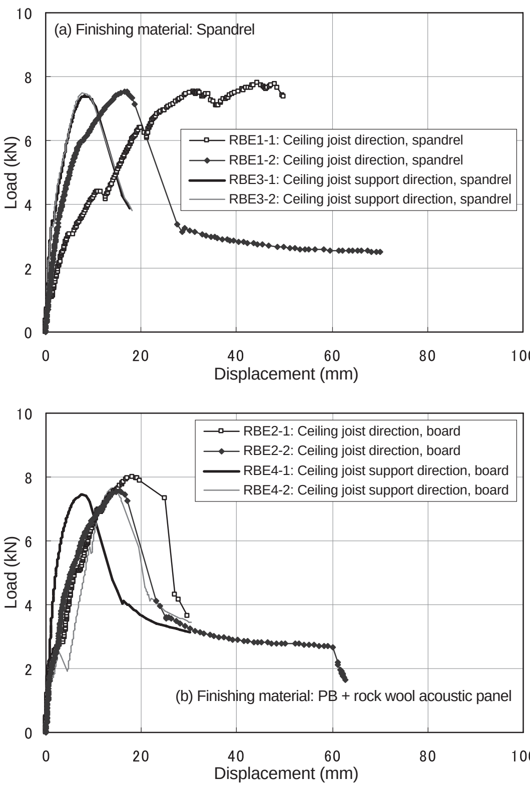


Fig. 9 Load - Displacement Relationship

3.2.3 Consideration

Table 4 shows a list of the test results. The maximum bearing force was more than 7,000 N with all of the specimens, regardless of the direction of load application and the type of finishing material. The load at δ1/100 deformation was twice to four times larger than that with a conventional aseismic ceiling.

Table 4 List of Test 2 Results

No.	Test No.	Specimen No.	Max. bearing force (N)	Displacement at max. bearing force (mm)	Load at δ1/100 displacement (N)	Load at δ1/100 displacement of conventional aseismic ceiling (N)
13	RBE1	RBE1-1	7795	44.5	5037	1820
14		RBE1-2	7547	16.5	7405	
15	RBE2	RBE2-1	7987	18.1	7610	
16		RBE2-2	7585	15.5	7542	
17	RBE3	RBE3-1	7395	8.3	4415	1576
18		RBE3-2	7490	7.7	3500	
19	RBE4	RBE4-1	7445	7.6	4437	
20		RBE4-2	7645	14.1	7497	

The reason for deformation of RBE1-1 before reaching its ultimate state could be that, as shown in Fig. 10, development C rotated and dug into the spandrel and the screws of the spandrel joint came off. This can be prevented by placing the end of development C in a manner that it avoids the joint.

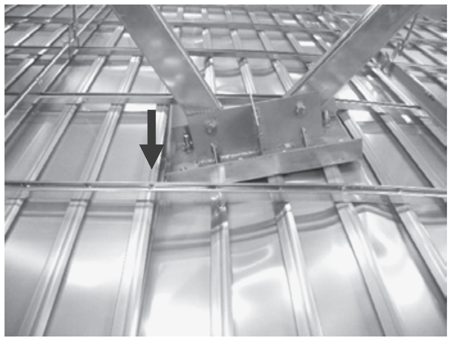


Fig. 10 Ultimate State of RBE1-1

With the specimens other than RBE1-1, buckling of the brace reached the ultimate state. We thus expect that using larger brace members will increase the strength of aseismic ceilings.

4 Conclusion

We developed two types of aseismic members for different usage, improving on the structural weakness of conventional aseismic ceilings. The results of static horizontal load tests on aseismic ceilings with the developed products proved that the developed products had aseismic performance roughly two times superior to that of conventional ceilings. Using the developed products will improve the bearing force per point of aseismic reinforcement and reduce the number of points where reinforcement members are installed, likely leading to reduction of the cost and time of aseismic improvement work for ceilings.

Reference:

1) Director of Building Guidance Division, Housing Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), "Geiyo Jishin Higai Chosa Hokoku no Sofu ni tsuite (Gijutsuteki Jogen) [in Japanese]" (ministerial notice MLIT HB BG No. 357, June 1, 2001)
2) Director of Building Guidance Division, Housing Bureau, MLIT, "Daikibo Kukan o Motsu Kenchikubutsu no Tenjo Horaku Taisaku ni tsuite (Gijutsuteki Jogen) [in Japanese]" (ministerial notice MLIT HB BG No. 1427, August 26, 2007)