Seismic Performance Evaluation of Nonstructural Components: Drywall Partitions

Tae-Hyung LEE, Mikiko KATO*, Tomohiro MATSUMIYA, Keiichiro SUITA, and Masayoshi NAKASHIMA

* Nikken Sekkei Ltd., Japan

Synopsis

In spite of its significance in the context of performance-based earthquake engineering, quantitative information on the seismic performance of nonstructural components is very limited. From among the nonstructural components that are significant in the economic losses in buildings, interior drywall partitions are selected for an experimental program. Four full-scale drywall partitions with light-gage steel stud framing were tested to observe damage to cyclic loading conditions. Effects of a door and an intersecting wall on the behavior of drywall partition are studied. Damage was concentrated to perimeter regions where gypsum boards made contacts with ceiling, floor, or columns. Dynamic loading did not amplify the damage to a drywall partition over the damage observed from the quasi-static test. Damage-repair cost relationships show that the repair cost reaches almost the initial cost under 2% radian interstory drift.

Keywords: nonstructural component, Performance-based earthquake engineering, drywall partition

1. Introduction

After many years of efforts by researchers and practitioners to develop performance-based earthquake engineering (PBEE) methodologies, it is now obvious that the issue of nonstructural components is one of the most critical elements of the PBEE methodology. Unlike structural components, most of the nonstructural components, including architectural, mechanical, electrical, and plumbing components, are vulnerable to a relatively low level of earthquake. According to reconnaissance reports for recent earthquakes, namely 1989 Loma Prieta, 1994 Northridge, and 2001 Nisqually earthquakes (Shephard et al. 1990; Hall 1995; Filiatrault et al. 2001), economic loss due to nonstructural components generally exceeds that due to structural components. Taghavi and Miranda (2003) studied the cost distribution of three types of buildings, namely offices, hotels, and hospitals, in terms of structural components, nonstructural components, and building contents. The cost of nonstructural components is the highest for all three types of buildings where its portion ranges from 48% and 70% of the total cost. According to Hirakawa and Kanda (1997), it is 40% for 210 reinforced concrete (RC) buildings damaged from the 1995 Hyogo-ken Nanbu earthquake, while that for structural components is also 40%. Consequently, it is widely agreed that the mitigation of nonstructural damage will dramatically improve the protection of structures from economic losses.

Among various nonstructural components, the interior architectural component is one of the most significant contributing components. Taghavi and Miranda (2003) reported that interior constructions and mechanical systems are the major source of cost (20-30% for different types of buildings) while electrical

systems and exterior closure cost almost 10% of the total based on their investigation for various building types, namely a mid-rise apartment, a hospital and office building, and a high-rise hotel. The other nonstructural components such as elevators, escalators, and roofing do not contribute more than 5% to the total nonstructural component cost.

Another important issue related to nonstructural components in earthquake engineering is that nonstructural component failure may be a significant threat to life safety. In addition to an indirect threat to life safety from closing hospitals, Rihal et al. (1998) pointed out a potential disaster of the theatre-like structure where several hundred square feet of plaster ceiling may fall on seating areas below during a large earthquake event.

Despite the significant amount of research already conducted within the framework of the PBEE methodology, there is limited information in the literature on the relationship between structural responses and nonstructural damage and consequences of the damage. Moreover, most of the existing information about the performance of nonstructural components is from previous earthquakes. Villaverde (1997) summarized previous experimental studies and field observations of various secondary structural elements, including mechanical and architectural components and building contents, and pointed out the scarcity of available experimental data.

Among various nonstructural components of buildings, this study focuses on the interior drywall partition with steel-stud framing used in typical Japanese buildings. A number of studies have been conducted on this type of component (Freeman 1977; Rihal 1982; Adhams et al. 1990; Serrett and Ogunfunmi 1996; Liew et al. 2002; McMullin and Merrick 2005). Most of them focused on evaluating the load-deformation relationship of drywall partitions in terms of the load-carrying capacity under quasi-static load, either monotonic or cyclic. Rihal (1982) and McMullin and Merrick (2005) investigated the damageability of drywall partitions using various damage thresholds. However, none of these previous studies considered the drywall partition specimens that were mounted on the primary structures such as floors, ceilings, and columns. They did not evaluate the repair costs corresponding with detailed damage thresholds, which is critical in PBEE.

The purpose of this study is to characterize the seismic performance of the drywall partitions typically used in Japanese building constructions. For a realistic representation, a full-scale drywall partition is mounted on a primary structural system. The relationship between the damage to a drywall partition and the structural responses such as the interstory drift are developed under quasi-static cyclic loading conditions. The repair cost corresponding to a specific interstory drift is estimated. The effects of the existence of a door, an intersecting wall, and a dynamic loading are also investigated.

2. Drywall Partition

2.1 General

The main role of the drywall partition is to provide a space that is separated from noise and fire. The selected type of the drywall partition, the light-gage steel-stud framing system sheathed by gypsum boards, is the most widely used interior partition wall for all types of building in Japan. It consists of runners, studs, and gypsum boards. Runners and studs made of steel are the framing components of the wall. This type of drywall partition is also commonly used in the United States of America for commercial buildings. However, design details such as the thickness and the number of layers of gypsum boards, and some of the installation procedures, are different from those of Japanese practice.

Two installation methods are available for the framing components. One is to install them in the ceiling, and the other is to install them on the beam or the floor slab. In general, the first method is used for residential buildings, and the latter is used for office buildings and hospitals. In this study, the latter method is used to install specimens. The following section describes the installation procedure of the drywall partition.

2.2 Installation of Drywall Partition

Before installing the drywall partition, base channels are fixed to floors and beams by screws. Runners are attached to the floor and beam by screws to form horizontal frames. A series of studs are attached to runners with a certain spacing (usually 450mm) to form vertical frames.

The general procedure of installing the partition wall is as follows:

1. Runners are bolted to the floor and beam (top and bottom beams, respectively, in the test).
2. Studs are attached to the runners to form vertical frames [Fig. 1(a)].

(a) studs   (b) the first layer

(c) the second layer   (d) joint mixture

Fig. 1 Installation procedure.
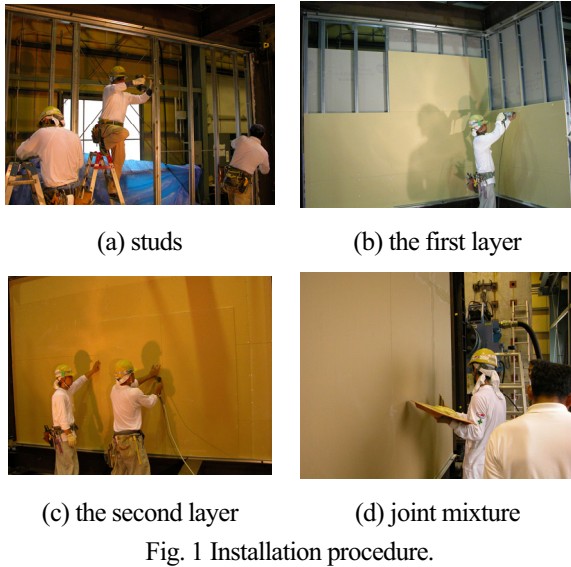
3. The first (inner) layer of gypsum boards is attached to studs by screws on each face of the drywall partition [Fig. 1(b)].

4. The second (outer) layer of gypsum boards is attached to the first layer of boards by glue and staples [Fig. 1(c)] on each face of the drywall partition.

5. Gaps between boards are sealed by the joint mixture [Fig. 1(d)].

It is noted that studs are not screwed to runners, while the gypsum boards and studs are securely attached to each other. When the building suffers story drift, e.g. by a seismic load, the studs and gypsum boards slide as runners move with the floor or the ceiling.

Therefore, the drywall partition is expected not to sustain damage until the side of the drywall partition is constrained by an intersecting wall or a structural column. Such failure was observed in the tests, as explicated below. Even though there is no code specification on the clearance of the drywall partition, 10-15mm is usually adopted in Japanese practice. On the other hand, it is common to fix steel studs to runners by screws in US practice.

When installing a partition with a door, two vertical channels are used to support the doorframe. Unlike studs, these channels are securely fixed to runners by screws. The clear spacing of the two channels equals the width of the doorframe so that the doorframe is fixed to these channels by screws.

2.3 Specimens

Four drywall partitions were built for the present experimental study. Fig. 2 shows design details of these specimens. Specimen No. 1 is a plain drywall partition with the dimensions of 2800mm (height) by 3950mm (width), constructed with the procedure described in the previous section. Specimen No. 2 is a drywall partition with a door (850mm by 2100mm). The wall dimensions are identical to those of specimen No. 1. Specimen No. 3 consists of two walls intersecting each other at a 90-degree angle. The width of the main wall (parallel to the loading direction) is 2975mm and that of the intersecting wall (orthogonal to the loading direction) is 1600mm, while the height of both walls is 2800mm.
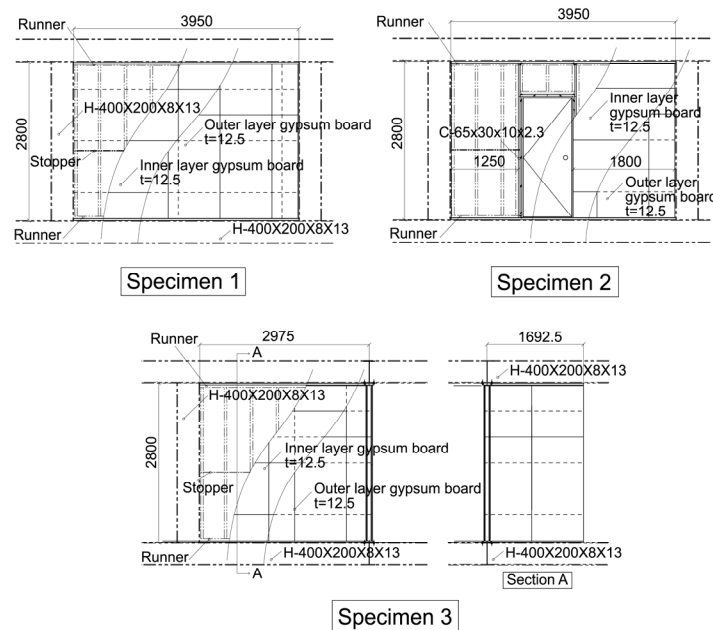
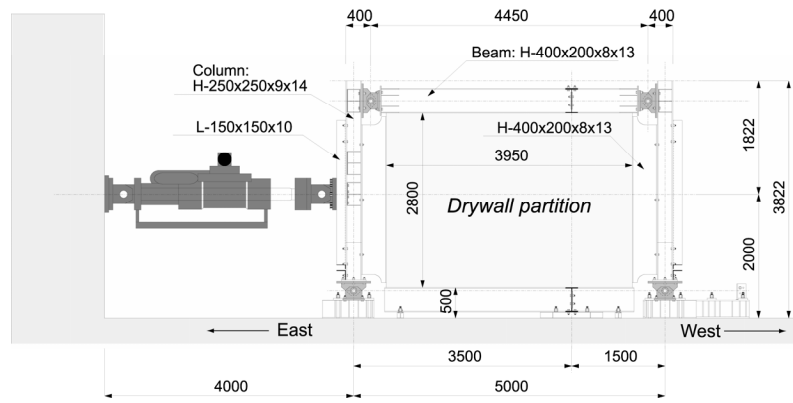

Fig. 2 Design details of specimens (unit: mm).

Fig. 3 Test setup (unit: mm).

Specimen No. 4 was constructed to study the effect of dynamic loading whose design is identical to Specimen No. 1. For base channels, this study used Japanese Industrial Standard 65 type; for runner, WR-65 (67X40X0.8); for stud, WS-65 (65X45X0.8); for stopper that connects studs laterally, WB-25 (25X10X1.2). The gypsum board whose dimensions are 910mm by 1820mm with 12.5mm thickness is made of gypsum and finished with paper on one face.

3. Test Setup and Procedure

It is assumed that the most critical structural response to partition walls is the story drift. Accordingly, the test setup is designed such that pure shear loading, either static or dynamic, is applied to the test specimen. Fig. 3 depicts the schematic of the test setup and its various details. The specimen was mounted on pin-connected beams and columns such that base channels were attached to the top and bottom beams. The clearance of 15mm between the drywall partition and the column was provided on each side (East and West) for all specimens except Specimen No. 3 where it applied only to the east side of the specimen. The hydraulic actuator was connected to the east column to provide the lateral loading.

Three rows of strain gauges were glued on one face (the north face) of the specimen to measure the strain of the gypsum board in the vertical direction. For Specimen No. 3, strain gauges were also glued on one face (the east face) of the orthogonal panel in the same pattern. One row was at the mid-height of the partition, another was 250mm above the bottom runner, and the last was 250mm below the top runner. The lateral space between two adjacent strain gauges was 455mm. No strain gauge was attached to the door panel in Specimen No. 2.

Fig. 4 shows the sequence of quasi-static cyclic loading. It applies to all specimens except for Specimen No. 4. After reaching the peak deformation of each cycle, both positive and negative, and reaching zero deformation, damage was inspected and recorded. A series of sinusoidal loading, two cycles with the period of 1 second (one cycle) and the amplitude of 1/400, 1/200 … and 1/10, the same as those specified in Fig. 4, was applied to specimen No. 4. At the end of each loading amplitude, i.e., every two cycles, damage to the specimen was inspected and recorded.
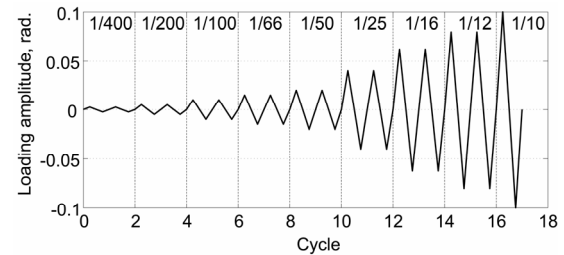

Fig. 4 Cyclic loading protocol.

4. Observations of Wall Damage

This section describes the damage to the specimens observed by eyeball inspection, which is followed by the analysis of strain measurements. Observed damage patterns include crushing of boards, sealing cracks, board cracks, and out-of-plane deformation of boards whose parts around screws were crushed. Fig. 5 shows pictures of various damage patterns of the drywall partition.

4.1 Damage to Specimen No. 1

No damage was observed in Specimen No. 1 as long as the story drift did not exceed 0.01 rad. The partition could slide without experiencing damage due to the connection detail of studs and runners and the initial gaps between the partition and the columns. The lateral rigid movement of the partition by 15mm (initial gap of one

side) in addition to the initial gap of 15mm on the other side prevented the partition from being damaged up to 30mm of the story drift that corresponds to 0.01 rad (30mm/2800mm). At 0.015 rad story drift, a room for the sliding was not available any more due to geometry and the column started to crush the neighboring gypsum board. Damage to the specimen is mainly due to compressions from the columns and beams, rather than the shear force. Fig. 6 shows a picture of Specimen No. 1 at the end of the last loading.

(a) crushing

(b) board crack

(c) sealing crack

(d) board detachment
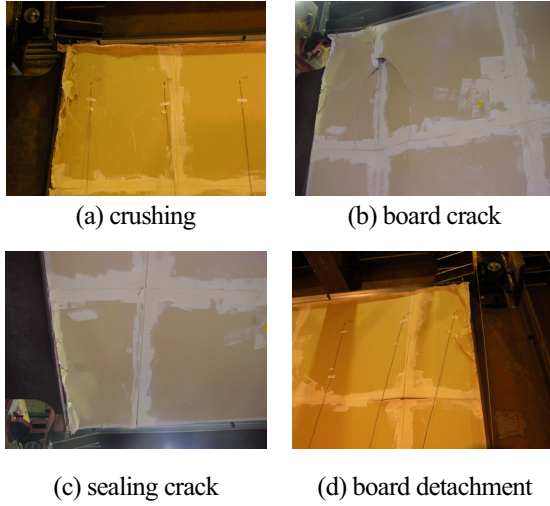
Fig. 5 Damage patterns.
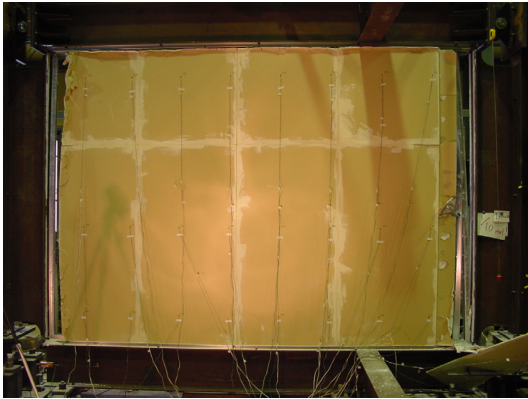
Fig. 6 Specimen No. 1 after the test.

It is noted that the damage is concentrated at the boundaries of the partition, particularly the four corners, while the inside portion of the partition only suffers from relatively minor damage. To support this argument, the average strains of the inside portion, the boundary and the four corners of the partition are compared in Fig. 7(a),

in which the values corresponding to peak rotations are plotted. The average strain of the boundary of the partition is more than twice as high as that of the inside up to the 0.06 rad story drift, where severe damage to the gypsum boards fails some of the strain gauges at the boundary. Moreover, the average strain of the four corners is about 50% higher than that of the boundary. Damage to Specimen No. 1 is depicted in Fig. 8 where the number in parentheses designates the loading amplitude in radian at which the corresponding damage occurs.
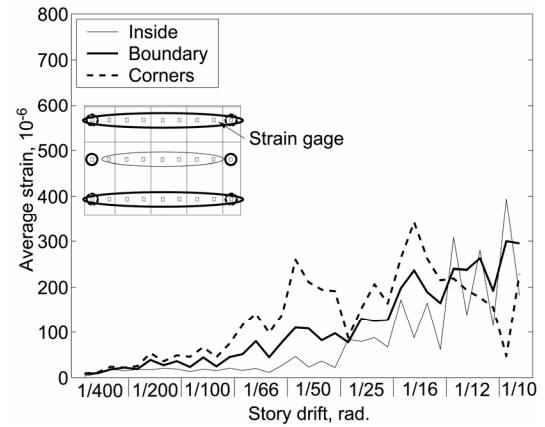

Fig. 7 Average strains of Specimen No. 1.

4.2 Damage to Specimen No. 2

The feature of Specimen No. 2 is the door in the partition. The functionality of the door is of interest as well as damage to the partition for the safety issue. During the test, the door was jammed at story drift of 0.01 rad. As shown in Fig. 9(a), the gap exists between the door panel and the doorframe. At the story drift of 0.01 rad that causes 0.006 rad shear distortion of the doorframe itself, the gap was closed because of the rotation of the door panel to cause the door to jam, as shown in Fig. 9(b). However, when the load was removed to the zero story drift, the door panel and the doorframe recovered their original shapes and the door was working. At the story drift of 0.02 rad, the door lock was broken as well as the door jammed due to the door panel's rotation, as shown in Fig. 9(c). It was not recovered even at the zero story drift and the door was permanently jammed. It is noted that the shear distortion of the doorframe that caused this was 0.01 rad.
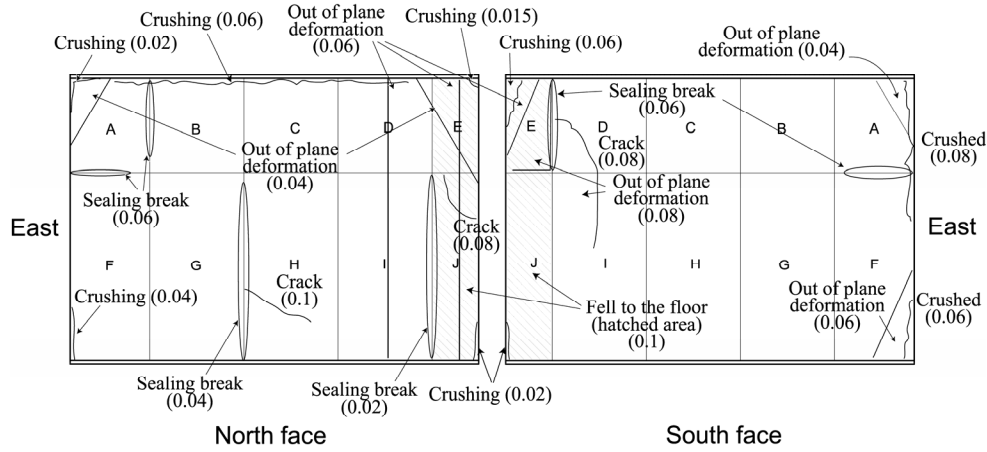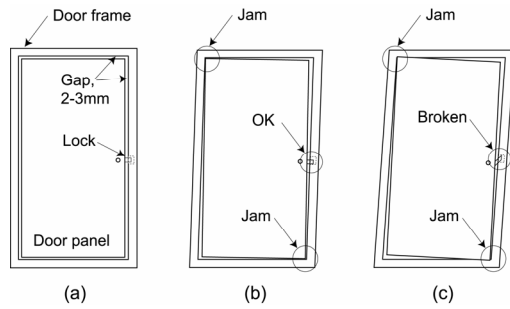
Fig. 8 Damage to Specimen No. 1.

Fig. 9 Functionality of the door in the drywall partition; (a) initial configuration of the door; (b) deformation of the door under 0.01 rad story drift; (c) deformation of the door under 0.02 rad story drift.

Fig. 10 Specimen No. 2 after the test.

Fig. 10 shows a picture of Specimen No. 2 after the test. It is clearly visible that the entire partition is completely divided into three panels by cracks: the left, above, and right side of the door. Fig. 11 shows the comparison of the average strains of the inside, boundary, and corners of the partition. Similar to Specimen No. 1, the corners suffer from higher strain than the other part of the partition up to the story drift of 0.02 where some of

the strain gauges at corners failed due to damage. Moreover, the boundary of the partition shows 150% higher strain than the inside. Damage to Specimen No. 2 is depicted in Fig. 12.
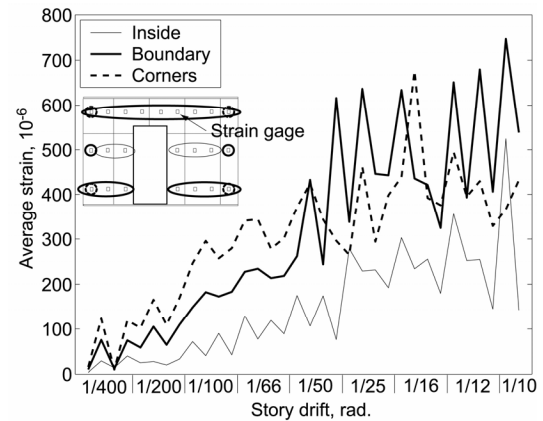

Fig. 11 Average strains of Specimen No. 2.

4.3 Damage to Specimen No. 3
The feature of Specimen No. 3 is an intersecting partition. The partition perpendicular to the loading direction is referred to as the orthogonal partition. The parallel (to the loading direction) partition did not show any significant damage up to story drift of 0.06 rad. At the next loading cycle (0.08 rad story drift) some of the gypsum boards were completely detached from studs and all the gypsum boards of the north face of the partition fell completely to the floor at the last loading cycle (0.1 rad). Fig. 13 shows the damage to Specimen No. 3. The damage to the orthogonal partition is relatively small. This is verified by the analysis of strain measurements.
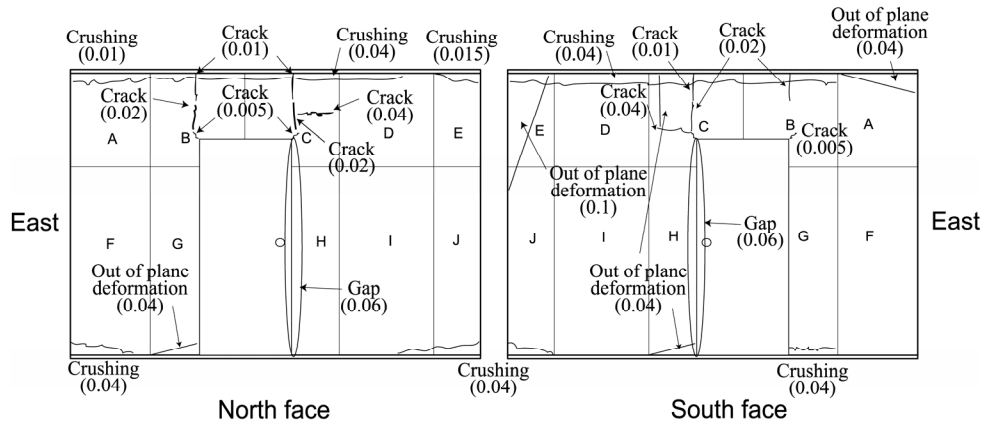
Fig. 12 Damage to Specimen No. 2.

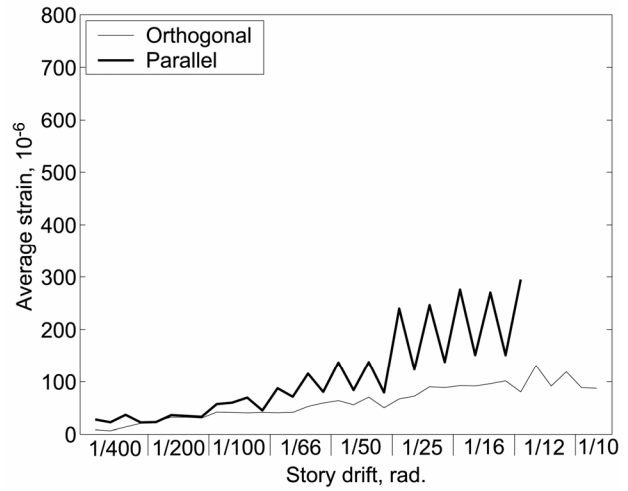Fig. 13 Specimen No. 3 after the test.

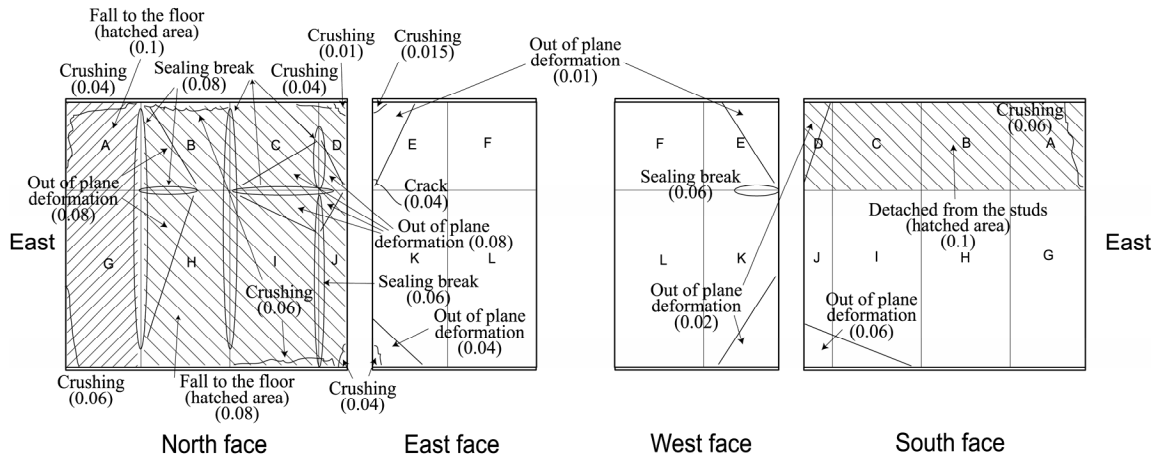Fig. 14 Average strains of Specimen No. 3.

Fig. 15 Damage to Specimen No. 3.

Fig. 14 shows average strains of the parallel and orthogonal partitions. It should be noted that strain measurements near the intersection of the two partitions are excluded in the computation of the average strains. The average strain in the parallel partition is twice as high as that in the orthogonal partition. Damage to Specimen No. 3 is depicted in Fig. 15.

4.4 Damage to Specimen No. 4
A series of dynamic loads, as described in a preceding section, is applied to Specimen No. 4, which is identical to Specimen No. 1 in design. Unlike the tests of the other specimens, damage inspection was carried out at the end of each loading cycle (two dynamic cycles with the same

amplitude of the story drift). The damage pattern is similar to that of Specimen No. 1 where the boundary of the partition is more damaged than the inside of the partition. Moreover, two gypsum boards were completely detached from the studs and fell to the floor. Fig. 16 shows average strains of the boundary, inside, and four corners of the partition. The trend of the plot is comparable to that of Specimen No. 1 in Fig. 7. A picture of Specimen No. 4 at the end of the test is shown in Fig. 17. Damage to Specimen No. 4 is depicted in Fig. 18.
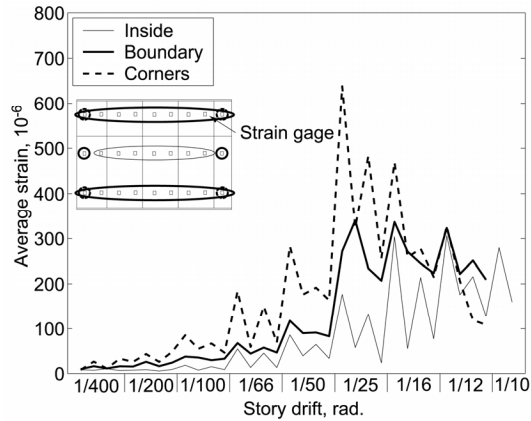

Fig. 17 Specimen No. 4 after the test.

Fig. 16 Average strains of Specimen No. 4.

5. Repair Cost Estimate

Throughout the series of loading tests, drywall partitions experts (manufacturers) were present at the test site and evaluated damage of the partitions at different loading levels. In addition, they provided opinions on whether the partitions should be repaired or replaced, if not intact. The relationship between the story drift and the damage to the partition in terms of the repair cost is developed.

Fig. 19 shows the ratio of the repair cost to the initial cost (referred to as the cost ratio) for Specimen Nos. 1, 2, and 3 with respect to the story drift. The initial cost includes two layers of gypsum boards, base steel frames, runners and studs, and the labor expense. The repair cost refers to the cost to replace the damaged part of the partition. It includes necessary material and labor expenses to repair the partition and the removal and disposal of the damaged part of the partition, so that the replacement cost exceeds the initial cost. It is noted that the initial costs of Specimen Nos. 2 and 3 are 77% and 19% higher than that of Specimen No. 1, respectively.

Specimen No. 1 need not be repaired as long as the story drift is not greater than 0.01 rad because it only slid without being damaged. Therefore, at story drifts of 0.005 rad and 0.01 rad, which are considered the expected demands for Levels 1 and 2 earthquakes in Japan, respectively, no repair was needed. At the story drift of 0.02 rad, the cost ratio is already as high as 0.94. At the story drift of 0.04, the repair cost exceeds the initial cost. From the story drift of 0.015 to 0.04 rad, only
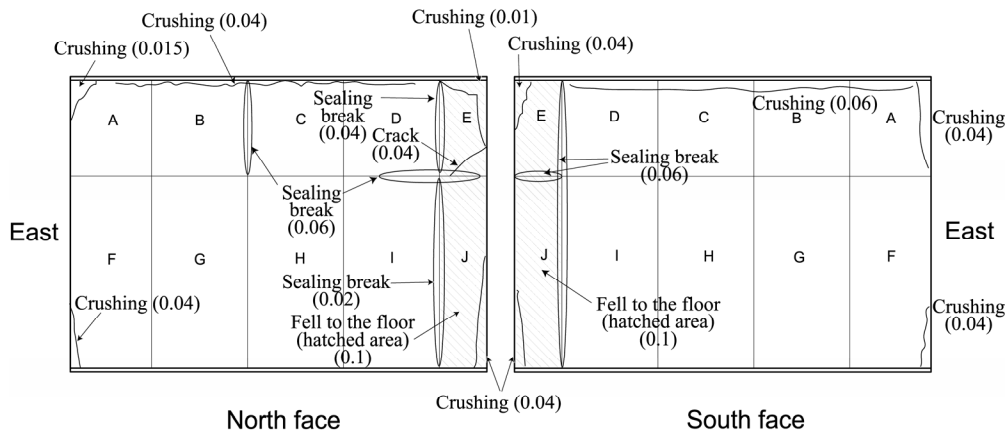

Fig. 18 Damage to Specimen No. 4.

gypsum boards are to be replaced. At the 0.06 rad story drift, all parts except for the base steel frame are to be replaced. After the 0.08 rad story drift, the whole wall needs to be replaced and the cost ratio is 2.36.
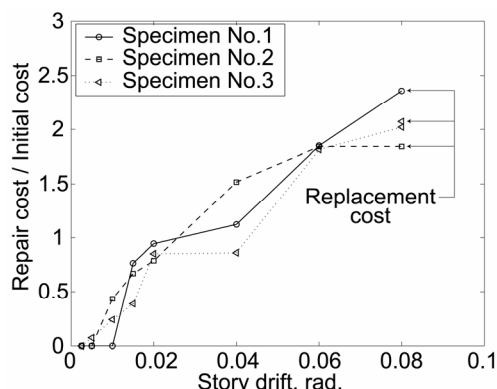

Fig. 19 Damage-repair cost relationship.

Specimen No. 2 need not be repaired as long as the story drift is not greater than 0.005 rad. Some cracks were observed at the story drift of 0.005, but they were considered insignificant and not requiring repair. At the story drift of 0.01 rad, the cost ratio is 0.43. The cost ratio is 0.79 at the story drift of 0.02 rad, which includes the replacement of the doorknob. At the story drift of 0.04 rad, the repair cost exceeds the initial cost. After the 0.04 rad story drift, the door needs to be replaced, which causes an additional rise in the repair cost. It is noted that 50% of the initial cost of this specimen is the installation of the door. After the 0.06 rad story drift, the whole partition needs to be replaced and the cost ratio is 1.84.

Specimen No. 3 needs to be repaired as long as the story drift is greater than 0.0025, which is earlier than any other specimen. This is caused by the damage to gypsum boards and joint mixtures near the intersection of the parallel and orthogonal partitions. At the story drift ratios of 0.005 rad and 0.01 rad, the cost ratios are 0.08 and 0.24, respectively. At the story drift of 0.02 rad, the cost ratio is 0.85. From the 0.02 to 0.04 rad story drift, the orthogonal partition also needs to be repaired. From the 0.06 rad story drift where the repair cost exceeds the initial cost, almost all parallel partition needs to be repaired. However, this specimen does not require the whole replacement of the partition whose cost ratio is 2.02 because some parts of the orthogonal partition are intact.

Overall, none of the specimens needs to be repaired as long as the story drift is not greater than 0.0025 rad. Specimen No. 1 could take the story drift of 0.01 rad

without being damaged due to the *sliding* of the partition, while the other specimens required repair at smaller story drifts than 0.01 rad because sliding was not allowed for them. After experiencing the 0.02 rad story drift, the repair cost almost reaches the initial cost of the partition where the average cost ratio of three specimens is 0.86. After the 0.08 rad story drift, the repair cost of all specimens reaches their replacement costs except for Specimen No. 3 where 98% of its replacement cost is required. The replacement costs of three specimens are about twice the initial costs where the average cost ratio is 2.1.

6. Load-Displacement Relationship

During the test, the load in the jack and the corresponding displacement that is under control are measured to investigate the load-displacement relationship of the specimen. The relationship between the story shear force and story drift for each specimen is shown in Fig. 20. The most important characteristics of the load-displacement relationship are pinching and stiffness degradation. Strength degradation is also observed in all three specimens where those of Specimen No. 1 in the negative loading and of Specimen No. 3 in the positive loading direction are distinctive.

The shear strengths, regardless of the direction of loading, are 72, 50 and 51 kN for Specimen Nos. 1, 2, and 3, respectively. These strengths do not seem negligible with respect to the structural strength expected for steel moment frames. For example, a wide-flange cross-section typically used in Japan for low to medium-rise steel moment frames, H-300x300x10x15, has a share capacity of about 250 kN in the strong axis bending. (Here, assumed was a column height of 4m, steel's yield stress of 300 MPa, and formation of plastic hinges at both ends of the column in double curvature bending.) The partitions' shear strengths reach greater than 20% the column shear capacity. In light of the damage pattern of the tested partitions, the source of the load-resisting mechanism of the partition is believed to be the compressive resistance of gypsum boards nailed to studs. The lateral resistance provided by partitions is of a great interest in the characterization of the ultimate resistance of steel frames. The information obtained from this study is still limited, and further examinations are needed for this purpose, including theoretical verifications of the load-resisting mechanism.

(a) Specimen No. 1

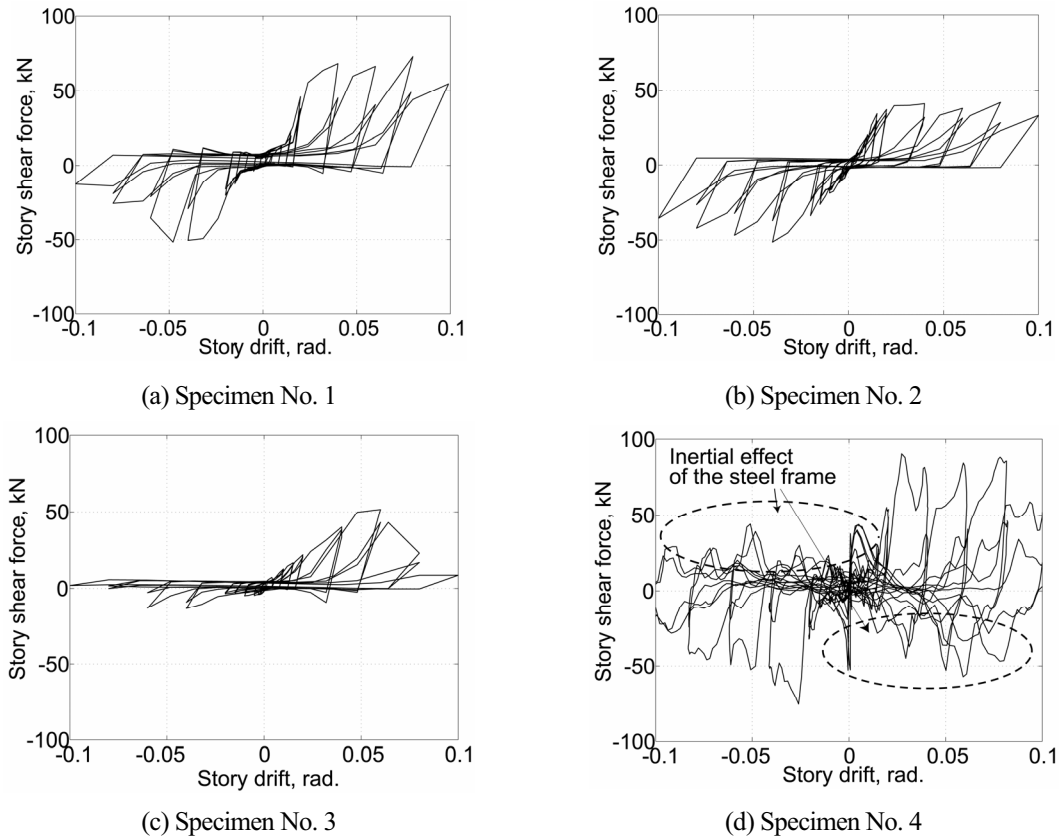(b) Specimen No. 2

(c) Specimen No. 3

(d) Specimen No. 4

Fig. 20 Story shear force vs. story drift relationships.

The load-displacement relationships of all three specimens are not symmetrical with respect to the loading direction. As shown in Fig. 20(a), peak strengths in the positive loading direction at each loading cycle are higher than the counterparts in the negative direction for Specimen No. 1. Moreover, the strength degradation in the negative direction is more severe than that in the positive direction. It is partially attributed to the notion that gypsum boards damaged in positive loading do not fully contribute to the corresponding load-carrying capacity in the negative direction.

For Specimen No. 2, peak strengths in the positive loading direction at each loading cycle are lower than their counterparts in the negative direction as shown in Fig. 20(b). In the positive loading, gypsum boards on the eastern side of the door act as the load-resisting component because the doorframe is fixed to the base channel and serves as the bearing support to the partition as shown in Fig. 21(a). On the other hand, when the load is reversed, gypsum boards on the western side of the door play the same role [Fig. 21(b)]. The difference in the bearing area at the bottom of the wall (1250mm and 1800mm for the positive and negative loadings, respectively) is likely to have caused the difference in the
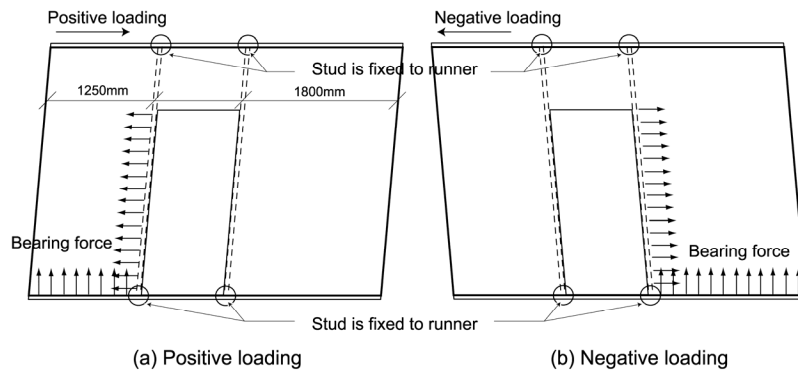

(a) Positive loading

(b) Negative loading

Fig. 21 Load-resisting mechanism of Specimen No. 2.

peak strength. Severe strength degradation is not observed, because the doorframe always acts as the bearing support in both directions.

Due to the design detail, the stud at the intersection of the two walls is fixed to the top and bottom runners for Specimen No. 3. In the positive loading, this stud tries to prevent the parallel partition from sliding. However, the gypsum boards and the other studs still manage to slip a small amount (relative to the cases of the other two specimens), because some parts of the gypsum boards are detached from the fixed stud. The increase in the amount of sliding due to the increase of the loading causes the strength degradation in the positive direction. On the other hand, when the load is reversed, the gap between the parallel partition and the eastern steel column is large enough not to be closed at the peak load of each cycle. Therefore the strength in the negative direction stays relatively low.

Fig. 20(d) for Specimen No. 4 shows inertial effect of the steel frame where the story shear force is increased when the loading direction is changed. However, it does not affect the damage of the wall as described earlier.

7. Conclusions and Future Extensions

Seismic performance of interior drywall partitions is experimentally evaluated and the corresponding repair cost is estimated. Four full-scale drywall partitions with light-gage steel stud framing sheathed with two layers of gypsum boards on both faces are constructed according to common Japanese building practice. Three different configurations of drywall partitions, namely plain partition, partition with a door, and partition with an intersecting wall, are considered to investigate the effect of design details on the behavior under quasi-static cyclic loadings, while the effect of the dynamic loading is investigated for the case of the plain partition.

Under the pure shear loading that simulates the story drift of the building, damages to drywall partitions are concentrated at perimeters where they are restrained by adjacent columns and beams or fixed studs for special configurations, such as a door and an intersecting wall. This implies that the design details affect the damage of the drywall partition. The test of the drywall partition with a door revealed that a door might jam at a relatively low story drift ratio (e.g. 2% radian). Dynamic loading effect on the damage of the drywall partition is negligible.

Repair cost estimates based on damage observations provide important quantitative information in the context of performance-based earthquake engineering. In the plain partition, damage and the consequent repair were avoided due to the loose connection between studs and runners up to the story drift of 0.01 rad. For all partitions, at the story drift ratio of 0.02 rad, the repair costs almost reach the initial costs of drywall partitions while they are twice as much as the initial costs at 0.08 rad story drift ratio. It confirms the importance of drywall partitions to the loss estimate of a building under seismic loadings.

In large drift angles, the tested partitions sustain shear resistance, which may not be negligible. The resistance may not be smaller than 20% of the structural resistance of steel moment frames. This statement, however, is preliminary, requiring more detailed research about the load-resisting mechanism of drywall partitions. The experimental project described in this paper is still ongoing, having been extended to tests of exterior cladding and window glasses, which will be reported later.

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非構造部材の耐震性能評価：間仕切壁

Lee Tae-Hyung・加登美喜子*・松宮智央・吹田啓一郎・中島正愛

* 株式会社日建設計

要旨

　非構造部材の耐震性能を定量化する目的で，間仕切り壁を設置した実大鋼構造フレーム実験を行った．ドアや直行壁に対する影響を含め，その損傷過程と補修費用の関係を検証した．石膏ボードの損傷は柱梁との接触部において顕著であり，動的な載荷による損傷と静的な載荷による損傷に差異は現れなかった．層間変形角0.02rad時において，ドアは鍵部の食い込みにより完全にロックされた．層間変形角0.02radを経験すると，補修費用が初期費用に達した．

キーワード: 非構造部材，性能規定型耐震設計，間仕切壁