

Seismic Behavior and Functional Loss of Swing Steel Doors within Partition Walls

Jiantao Huang^{1,*}, Masahiro Kurata¹

¹Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

Abstract

Doors, with a focus on swing steel doors in this study, serve as critical passageways for escape and rescue during earthquakes. However, operational difficulties with doors have been reported in existing studies. Despite this, the functional loss of doors has not received sufficient attention. Previous experiments have only briefly documented the observed phenomena, as doors were considered ancillary components of partition walls. Rotation has been regarded as the mechanism underlying the functional loss of doors, yet it fails to fully account for the experimental phenomena. The assessment of door functional loss has traditionally been based on the door's state, neglecting the physical strength of users. Therefore, this study investigates the functional loss of doors through a quasi-static test, exploring the associated phenomena, mechanisms, and consequences. A well-designed test program ensures that the results realistically reflect engineering conditions. The phenomena revealed variations in the gaps within the door across different positions and orientations. A mechanism combining rigid body motions and deformations was developed and validated to elucidate the functional loss of doors. By considering the physical strength of users, the functional loss of doors and the effects of improvements were reasonably assessed. The findings are anticipated to be applied in industrial manufacturing and post-earthquake rescue efforts.

Author keywords

Door, Functional loss, Quasi-static test, Mechanism, Seismic behavior, Partition wall

* Correspondence: Disaster Prevention Research Institute, Kyoto University, Uji, 611-0011, Japan
E-mail addresses: huang.jiantao.z19@kyoto-u.jp

1. Introduction

Swing steel doors (hereinafter referred to as doors) are widely used in residential and office buildings, which are typically densely populated. Doors serve as critical escape and rescue routes during earthquakes (FEMA 2019). As a result, opening doors becomes a safety action during seismic events (Fujinawa and Noda 2013; Nakayachi et al. 2019). However, many studies (Calayir et al. 2022; Cook et al. 2022; Lee et al. 2007; McCormick et al. 2008; Mulligan et al. 2022; Wang et al. 2016; Yagi et al. 2024) have reported cases of doors jamming during earthquakes. Moreover, a simulation (Maeda et al. 2018) demonstrated that 16.9% of steel structures in a specific region of Japan experienced difficulties in opening doors during a Nankai megathrust earthquake. Although the functional loss of doors poses a serious threat to life safety (McCormick et al. 2008; Yagi et al. 2024), and the Life Safety Nonstructural Performance Level is found in standards (ATC 2003; ASCE 2014, 2017; FEMA 1997), this issue has received limited attention in terms of its phenomena, mechanisms, and consequences.

In previous experiments (Huang and Kurata 2025; Lee et al. 2007; McCormick et al. 2008; Mulligan et al. 2022; Wang et al. 2016), doors were treated as adjuncts to partition walls, although doors were classified as a distinct category (ASCE 2014, 2017; FEMA 2018; Taghavi and Miranda 2003), resulting in the related phenomena being only briefly mentioned. For example, the gap in doors widened, and the screws fell off (Wang et al. 2016). However, such damage does not directly reflect the impact on the door's functionality as a passageway. Damage that directly impairs door functionality, such as door frame deformation (Wang et al. 2016) and door lock failure (Huang and Kurata 2025; Lee et al. 2007), is difficult to observe visually due to the subtlety of the deformation and location inside the door. Although one study (Lee et al. 2007) reported the jamming of the door plate under a specific loading, the direction of jamming during the loading was not

recorded, potentially leading to varying consequences. Therefore, a detailed phenomenon record is required to preliminarily reflect the functional loss of doors.

The mechanism causing the door plate to become jammed is attributed to the rotation of the door plate (Lee et al. 2007; Yagi et al. 2024), even though the source driving this rotation has not been elucidated. However, considering solely the rotation of the door plate fails to fully explain the phenomena observed in existing experiments (Lee et al. 2007; Yagi et al. 2024). Fig. 1(a) illustrates a phenomenon from a study (Lee et al. 2007), showing a narrowing of the horizontal gap at the bottom-left corner. However, the rotation of the door plate does not result in the horizontal narrowing at the bottom-left corner, as depicted in Fig. 1(b). Thus, although rotation accounts for certain phenomena (Lee et al. 2007), such as the narrowing of the vertical gap at the top-right corner, it does not provide a comprehensive explanation. In fact, Fig. 1(a) implicitly suggests that the deformation of the door frame should be considered as part of the mechanism. Nevertheless, the narrowing of the horizontal gap at the lower left corner remains unexplained. Therefore, developing a comprehensive mechanism for elucidating the functional loss of the door is necessary.

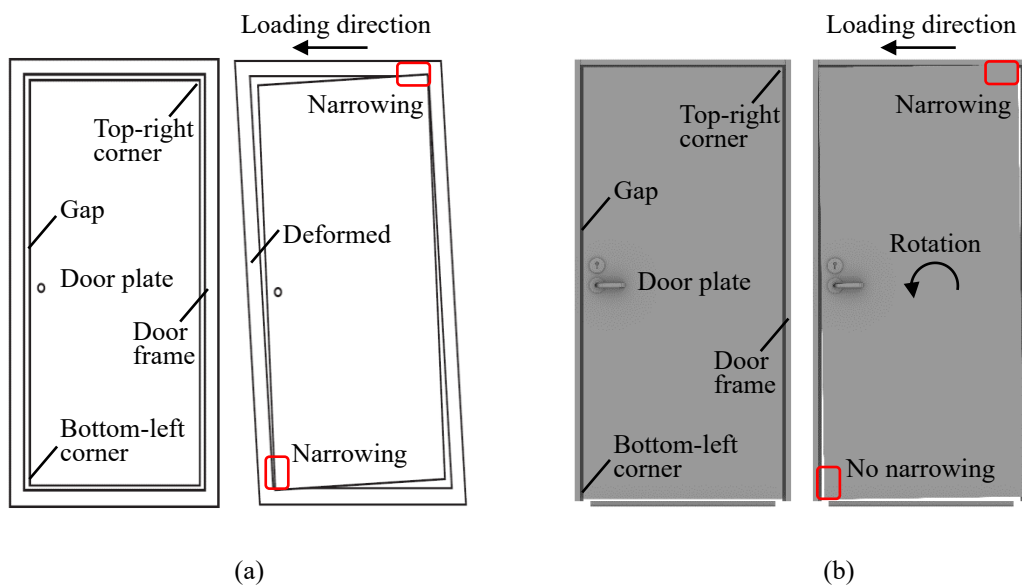


Fig. 1. Mechanism for phenomena: (a) Experimental phenomena (Lee et al. 2007); (b) Rotation as a mechanism

During seismic events, doors provide a passageway of escape and rescue through their opening. Consequently, existing studies (McCormick et al. 2008; Yagi et al. 2024) have identified difficulties in door operation as a functional loss. Such operational difficulties in experiments are manifested as door plates jamming and door locks failing (Lee et al. 2007; Wang et al. 2016). Taking into account the severity of damage and its impact on functionality, one report (Wang et al. 2016) classifies door damage into three states. Additionally, based on the classification of doors into three levels according to their deformations (JSA 2021), a study expresses the ease of door operation through story drifts (Maeda et al. 2018). However, existing investigations have relied solely on the direct (Lee et al. 2007; Wang et al. 2016) or indirect (Maeda et al. 2018) states of the door as indicators of functional loss, neglecting the primary agent of door operation—the users. Since functional loss is oriented toward the users, neglecting their role results in an inadequate assessment of functional loss. Therefore, a user-centered assessment for the functional loss of doors needs to be proposed.

To investigate the functional loss of doors, this study analyzes the phenomena, mechanisms, and consequences based on the results of a quasi-static test. In the experiment, a door is embedded within a partition wall to replicate actual engineering conditions, and the adoption of a mixed loading protocol ensures that the seismic behavior of the door accounts for damage to the partition wall. Firstly, the variations in gaps within the door are meticulously documented across different positions and orientations. Subsequently, data collected through an image-based displacement measurement system is utilized to propose and validate the mechanisms underlying the functional loss of the doors. Finally, the functional loss of the door and the effectiveness of an improvement are assessed from an ergonomic perspective. The results achieve a reciprocal correspondence among phenomena, mechanisms, and consequences, with the expectation of contributing to improvements in door construction and post-earthquake rescue efforts.

2. Quasi-Static Test

2.1 Door Specimen in A Partition Wall

To realistically test the seismic behavior of doors, a single door specimen was embedded in a 2920 mm × 2890 mm partition wall, as shown in Fig. 2. This type of partition wall is widely used in buildings (Menegon et al. 2023, 2024; Pali et al. 2018; Petrone et al. 2017; Yang and Kishiki 2024). The components (runner, stud, brace, clip, and panel) and their connections in the partition wall used in the experiment follow typical Japanese construction practices (JSA 2020; Huang and Kurata 2025; Huang et al. 2023, 2024). The partition wall was installed within a steel frame, bordered by beams, a column, and a stud column, with the runners rigidly connected to the beams. Unlike the columns, which were fixed at both ends, the stud column was hinged at the top end.

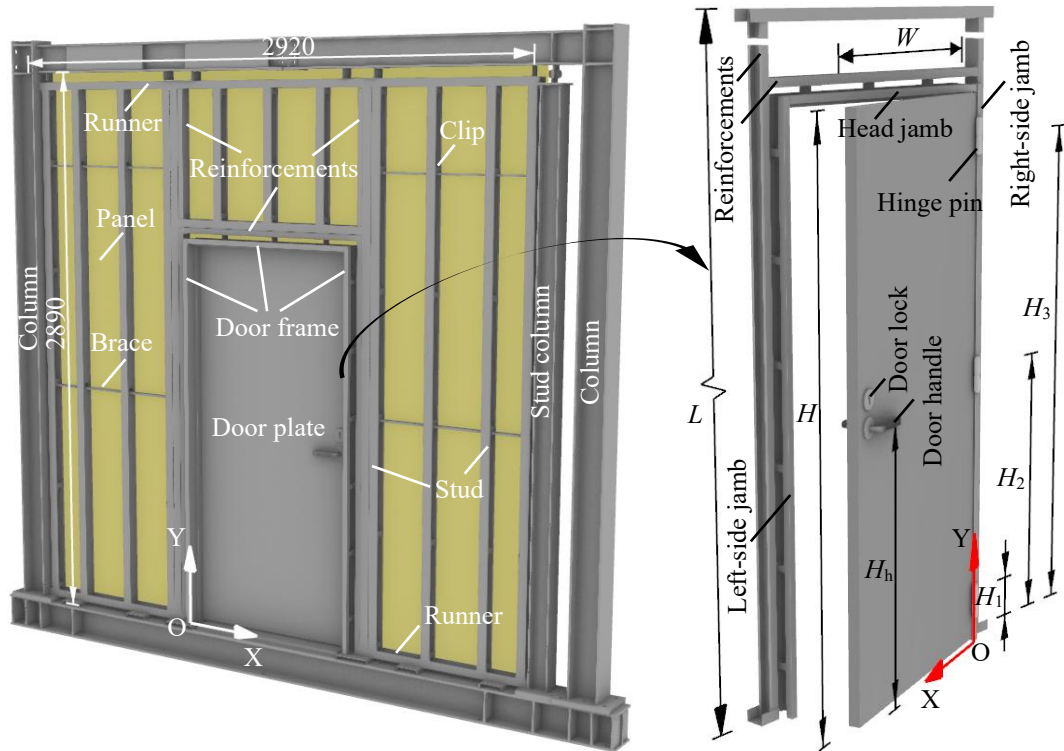


Fig. 2. Door specimen in a typical Japanese partition wall (unit: mm)

The door comprises a door plate, a door frame, and reinforcements, constructed in accordance with Japanese Industrial Standards (JSA 2021), ensuring its representativeness. The three sides of the door frame are designated as the head jamb, left-side jamb, and right-side jamb, and the gaps with the door plate take fire resistance and construction tolerances into consideration. For example, the side gap is 1/8 inch (3.175 mm) (NFPA 2022), and the construction tolerance is 2 mm (AQSIQ and SAC 2008). The door lock and door handle are installed on the door plate. The bottom ends of the door frame and the vertical reinforcements are rigidly connected to the beam, which serves as the ground. The top ends of the vertical reinforcements are fixed to the runner within the partition wall using screws. The connection between the door frame and the surrounding panels is characterized by contact without mechanical fastening. The perimeter of the door frame and the reinforcements are secured using connectors. The door plate is connected to the door frame by three hinge pins, which constrain the degrees of freedom in-plane while allowing rotation out-of-plane. The height of the vertical reinforcements is denoted as L . The dimensions of the door plate are specified as $W \times H$, with the height of the door handle indicated as H_h . The heights of the hinge pins at the bottom, middle, and top are represented by H_1 , H_2 , and H_3 , respectively. Table 1 presents the specific dimensions of the single specimen used in the experiment.

Table 1. Dimensions of the specimen (unit: mm)

Parts	Reinforcements	Door plate & Door handle			Hinge pins		
Parameters	L	W	H	H_h	H_1	H_2	H_3
Values	2890	900	2000	1000	150	1000	1850

2.2 Mixed Loading Protocol

Story drift ratios (SDRs) are considered a common engineering demand parameter for doors and partition walls, as both serve as drift-sensitive nonstructural components (ASCE 2014; Taghavi and Miranda 2003).

Consequently, a drift-controlled loading protocol is employed to reflect SDRs for residual in engineering. The embedding of doors within partition walls means that the damage to partition walls affects the operability of the doors. Therefore, the loading protocol must be capable of simultaneously replicating the behavior of both doors and partition walls during earthquakes.

A mixed loading protocol that accounts for both doors and partition walls is employed, as illustrated in Fig.

3. The loading is applied in the in-plane horizontal direction, excluding the contribution of vertical seismic effects. The mixed loading protocol consists of two parts: one for loading the door and the other for loading the partition wall. To evaluate the operability of the door during earthquakes, the International Organization for Standardization (ISO) (ISO 2007b) recommends eight loading steps, corresponding to SDRs ranging from 0.25% to 1.67%. To ensure that partition walls fully exhibit damage, the Federal Emergency Management Agency (FEMA 2007) suggests a loading protocol with increments of 1.4 times the previous step. According to an existing study (Huang and Kurata 2025), partition walls with doors occur damage before the minimum loading step for the door is reached, thus the loading for the door should commence after the initial loading of the partition wall. Upon completion of a loading step for doors, loading of both the door and the partition wall continues until the corresponding loading step for partition walls is reached, such as the fifth loading step for doors and the ninth loading step for partition walls. After completing the maximum loading step for the door, the loading of the partition wall proceeds as an excessive load, allowing further exploration of door operability if the door can still be easily opened when the SDR reaches 1.67%. As a result, the loading for the door is positioned in the middle of the partition wall's loading, better reflecting the seismic behavior of doors embedded in partition walls.

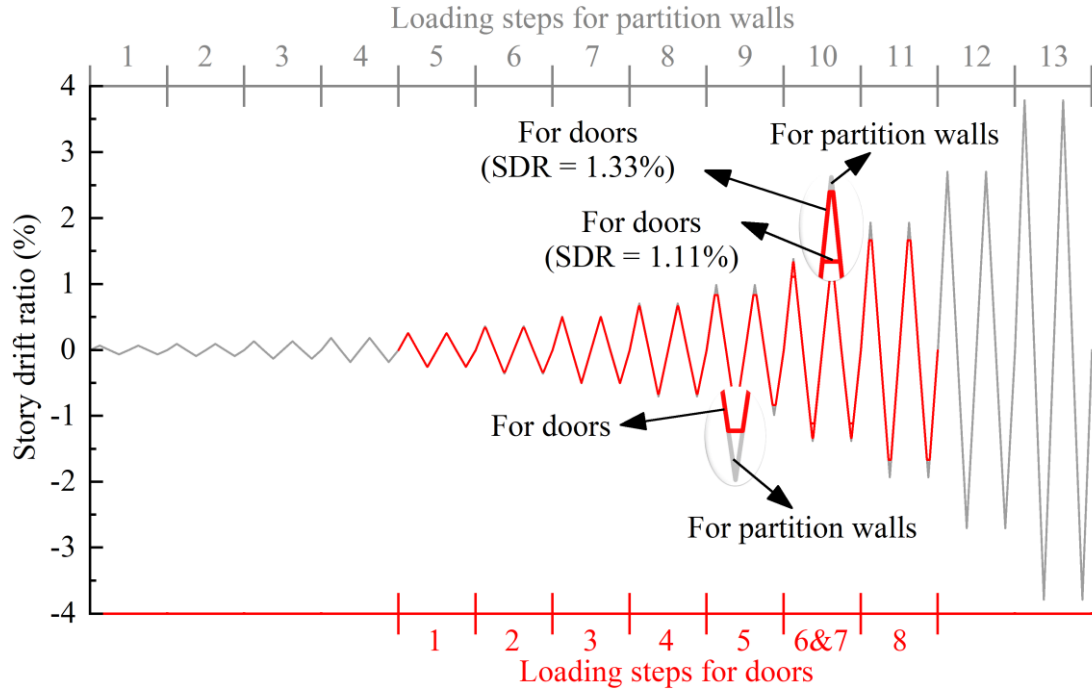


Fig. 3. Mixed loading protocol

2.3 Measurement

An image-based displacement measurement system with an accuracy of 0.1 mm was employed to monitor the displacement of the door, as illustrated in Fig. 4. The system, including markers and cameras, is calibrated by the markers placed on the base of the steel frame. Furthermore, the system's accuracy is maintained throughout the measurement process by accounting for the marker positions and camera perspectives before and after loading. Two cameras were positioned in front of the specimen to capture the markers, and the displacements of the markers were obtained by tracking the changes in their coordinates. Five markers, labeled M_1 to M_5 , were used in the experiment. M_1 and M_2 were placed at the corners of the door plate, while M_3 – M_5 were positioned at the door frame. The displacements of M_1 – M_5 in the horizontal and vertical directions were denoted as d_{x1} – d_{x5} and d_{y1} – d_{y5} , respectively.

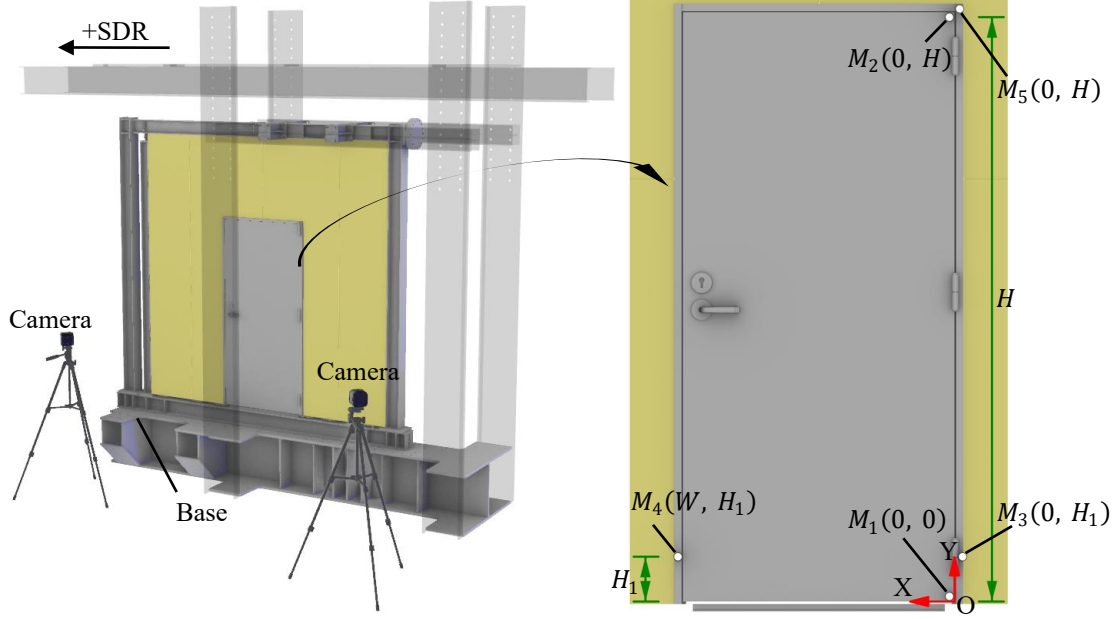


Fig. 4. Measurement by an image-based displacement measurement system

Since the objective of the measurements is to obtain displacements, the differences at nearby locations are negligible, allowing the displacements at these proximate markers to be equated, as reflected in the equivalence of the coordinates. The x-coordinates of M_1 , M_2 , M_3 , and M_5 are approximated to 0 due to their horizontal projections being close to the origin O. The x-coordinate of M_4 , being near the width of the door plate, is approximated as W . Similarly, the y-coordinate of M_1 is approximated to 0. The vertical projections of M_2 and M_5 are closely aligned, leading to their y-coordinates are both considered to be H .

Based on the construction of the door, M_1 and M_2 were placed on the right side to effectively mitigate the localized interference caused by the compression between the door plate and the side jambs, ensuring that their displacements reflect the rigid body motions of the door plate. The deformation of the door frame at the connection with the bottom of the door plate is represented by d_{x3} , and the deformation of the left-side jamb at the same height is represented by d_{x4} . M_5 was located at the junction of the right-side jamb and the head jamb, thus d_{x5} and d_{y5} correspond to the deformations at the ends of the right-side jamb and head jamb,

respectively.

Although ISO (2007b) provides an arrangement for measurement points, it places all measurement points on the door frame, which only reflects the deformation of the door frame, albeit implicitly incorporating the effect of the door plate. Compared to the ISO measurement arrangement, the measurement arrangement in this study not only considers the deformation of the door frame but also intuitively captures the relationship between the door frame and the door plate.

In addition, a spring dynamometer with a capacity of 600 N and an accuracy of 5 N was utilized to measure the pulling force required to open the door during loading. Throughout the testing process, the spring dynamometer was maintained in a horizontal alignment with the door handle.

3. Experimental Phenomenon

The width of the gap between the door plate and the door frame varied during the experiment, as shown in Fig. 5. Although the gap may become narrower, wider, or remain initial, this study focuses on the phenomenon of gap narrowing. Because a narrower gap impairs the functionality of door operation, which consequently affects post-earthquake evacuation and rescue efforts. Based on the extent of gap narrowing, the phenomenon is classified into two stages: gap reduction and gap closure. The former refers to a reduction in gap width by at least 1 mm but not to zero, and the latter denotes the complete closure of the gap with zero width. The trend of gap reduction serves as an indicator for predicting the occurrence of gap closure under increased loading.

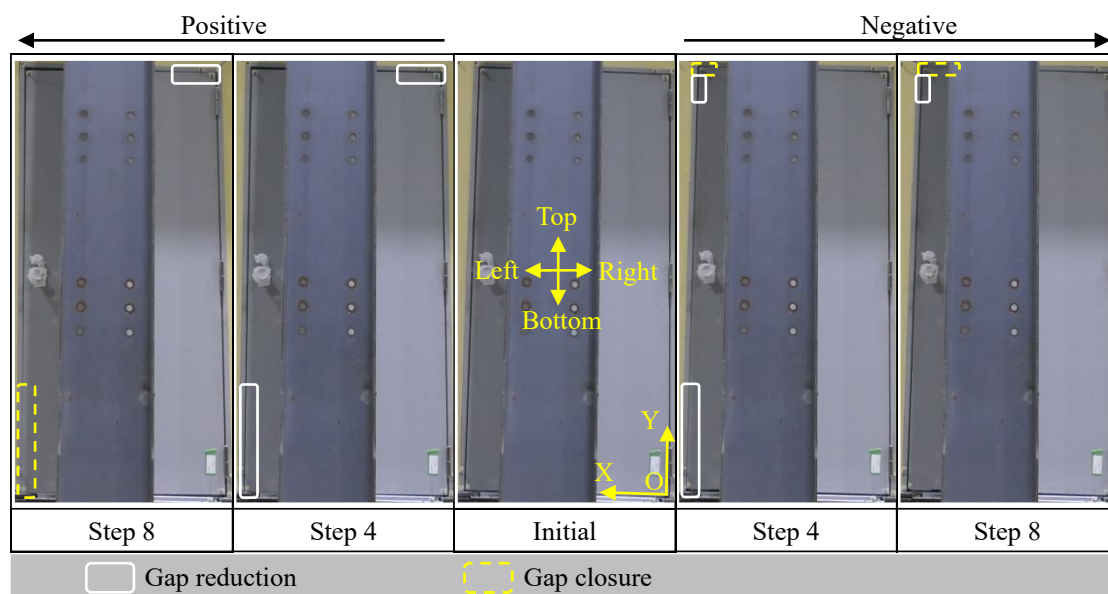


Fig. 5. Experimental phenomenon (examples at mid-loading and final loading steps for doors)

Fig. 5 documents the locations where gap narrowing occurs, which are influenced by both the direction and magnitude of the applied loading. Under positive SDRs, gap reduction or closure occurs at the bottom-left and top-right corners, with the trend—such as in step 4 and step 8—remaining consistent. Under negative SDRs, gap reduction or closure is observed at the bottom-left and top-left corners; however, the trend in the bottom-left corner changes under larger loads, such as in step 8. The gap along the right side in the X direction showed minimal variation during loading, owing to the connection of the hinge pins.

In response to the affected locations shown in Fig. 5, Fig. 6 illustrates the variation of the gap at different locations along different directions as SDRs increase. Under positive SDRs, gap narrowing occurs at the bottom-left corner in both the X and Y directions, and at the top-right corner in the Y direction. As the SDRs increase, the gap at the bottom-left corner transitions from reduction to closure, occurring in the X and Y directions at steps 5 and 7, respectively. In the top-right corner, gap reduction in the Y direction begins at step 6. For negative SDRs, gap narrowing is observed at the top-left corner in both the X and Y directions, and at the bottom-left corner in the X direction. The top-left corner shows gap reduction as SDRs increase, with closure in

the Y direction occurring at step 3. However, the trend of the gap at the bottom-left corner in the X direction changes with increasing SDRs, transitioning from gap reduction back to its initial width at step 6.

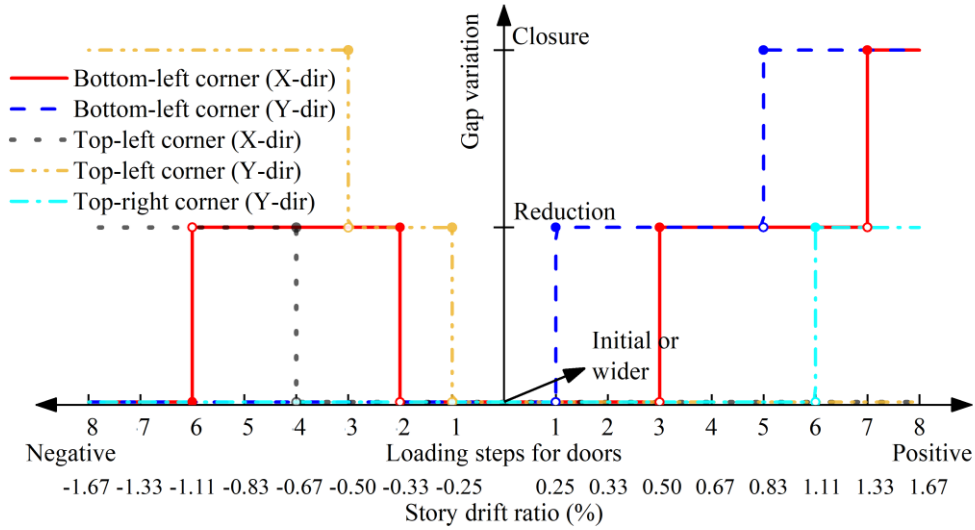


Fig. 6. Variation in the gaps between the door frame and door plate

4. Mechanism of Functional Loss

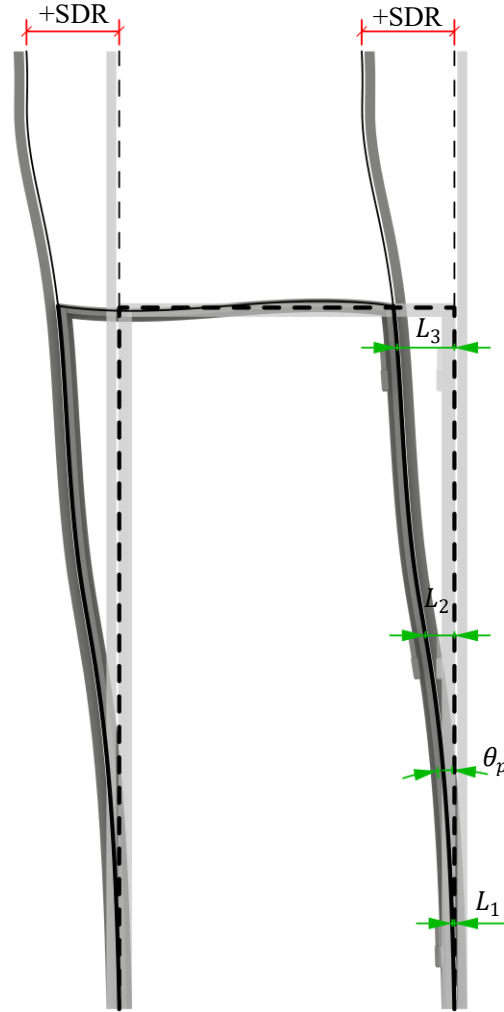
4.1 Mechanism Proposal

The diversity of experimental phenomena suggests the presence of multiple influencing factors for gap variation. The door frame and reinforcements are deformed under SDRs (Huang and Kurata 2025), with the deformations being affected by the panels. Since the door plate is only connected to the right-side jamb in the horizontal direction, the position of the door plate is intrinsically linked to the deformation of the door frame. Given that the interior of the door plate has been reinforced, it is treated as a rigid body, with its position represented by rigid body motion, encompassing both translation and rotation. Additionally, it is assumed that the ground remains undeformed. Overall, the mechanism in this study accounts for the deformation of the door frame and the rigid body motions of the door plate as influencing factors.

The deformation of the door frame has two effects. First, it influences the horizontal and vertical spacing

between the door frame and the door plate through the left-side jamb and head jamb, respectively. Second, it drives the rigid body motions of the door plate via the right-side jamb, as illustrated in Fig. 7. The deformation of the right-side jamb induces the rigid body motions of the door plate through three hinge pins located at different heights, with their displacements marked as L_1 – L_3 , considering only the deformation of the right-side jamb. However, when accounting for the door plate, L_3 cannot be fully realized due to the constraints imposed by L_1 through the door plate as an intermediary. Conversely, L_1 is elongated under the influence of L_3 , thereby controlling the translation of the door plate. The differences among L_1 – L_3 are represented by the angle θ_p . Although θ_p cannot be fully realized when considering the door plate, it governs the rotation of the door plate.

During the loading process, the relative position of the deformed left-side and head jambs to the door plate after rigid body motions governs the gap width, as illustrated in Fig. 8. Under positive SDRs, the rotation of the door plate results in the gap narrowing at the bottom-left corner in the Y direction, assuming the ground remains undeformed. Concurrently, in the X direction, the rotation of the door plate causes the bottom-left corner of the door plate to move away from the left-side jamb, while the top-left corner approaches the left-side jamb. However, the deformation of the left-side jamb is minimal at the lower portion, and the translation of the door plate leads to the gap narrowing at the bottom-left corner in the X direction. The deformation of the left-side jamb is large at the upper portion, preventing the gap at the top-left corner in the X direction from narrowing. The gap at the top-right corner in the Y direction narrows with the increasing rotation of the door plate, even considering the deformation of the head jamb. For the gap at the top-left corner in the Y direction, both the deformation of the head jamb and the rotation of the door plate prevent it from narrowing. Overall, under positive loading, and with reference to the deformation of the door frame, the horizontal gaps are governed by the translation of the door plate, and the vertical gaps are controlled by the rotation of the door plate.



242

243

Fig. 7. Deformation of the door frame without considering the door plate

244

245

246

247

248

249

250

Under negative SDRs, the rotation of the door plate causes a narrowing of the gap at the top-left corner in the Y direction. Meanwhile, the rotation ensures that the gaps at both the bottom-left corner and the top-right corner in the Y direction do not become narrower. The rotation of the door plate, coupled with the slight deformation of the lower portion of the left-side jamb, results in a narrowing of the gap at the bottom-left corner in the X direction. However, as the door plate translates, the gap at the bottom-left corner in the X direction continuously widens, thus altering the trend of gap variation. Although the rotation and translation cause the

door plate to move away from the left-side jamb, the increasing deformation of the upper portion of the left-side jamb leads to a gap reduction at the top-left corner in the X direction. Overall, under negative loading, and with reference to the deformation of the door frame, the horizontal gaps are jointly governed by the translation and rotation of the door plate, and the vertical gaps are solely controlled by the rotation of the door plate.

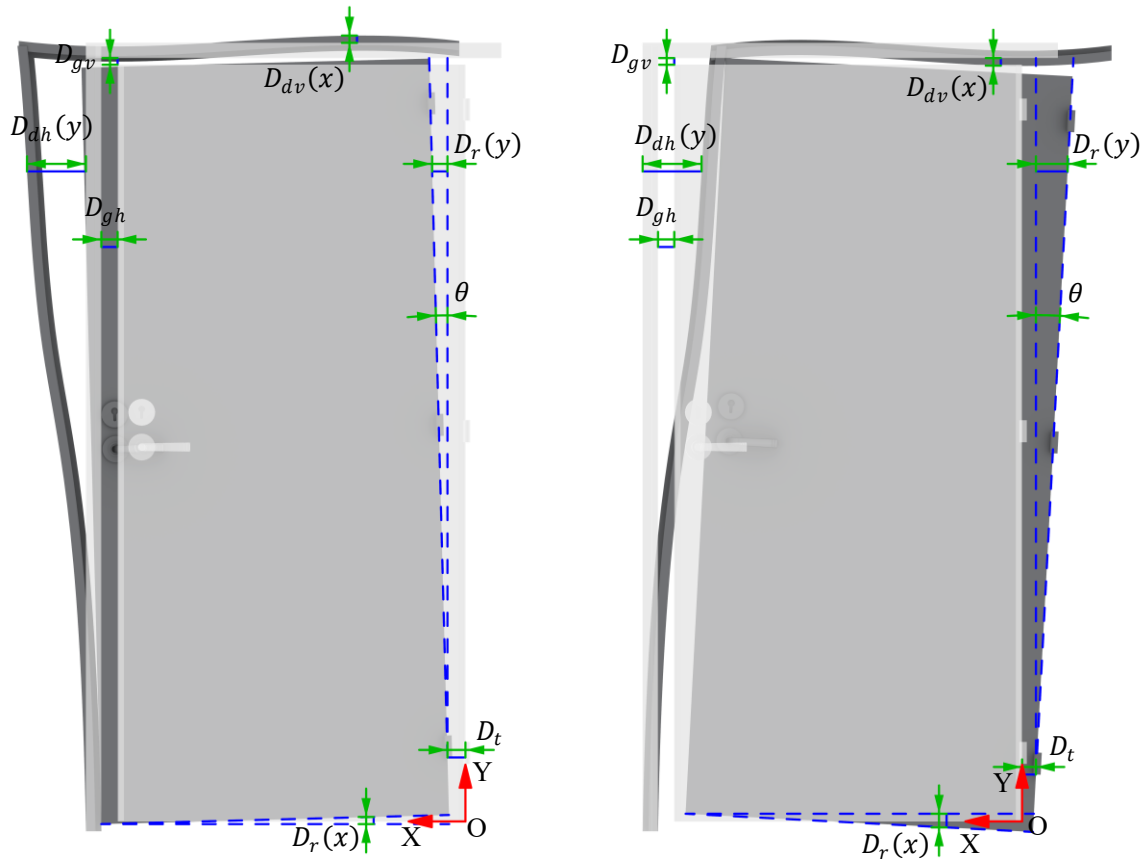


Fig. 8. Relative position of the door frame to the door plate: (a) Under positive SDRs; (b) Under negative SDRs

Although there are diversities in the deformation of the left-side and head jambs and the rigid body motions of the door plate, the relative positions of the door frame and the door plate are uniformly expressed as Equations (1) and (2). Furthermore, from an engineering perspective, Equations (1) and (2) consistently represent the relative positions, even in the presence of design variations such as differences in the height of the

partition wall, the position of the door within the partition wall and dimensional parameters of the door, which only alter the numerical values of the terms in the equations. Similarly, the vertical seismic effects neglected in the experiment influenced the numerical values of door frame deformation, resulting in variations in the observed phenomena and the effectiveness of improvements rather than altering the expression of relative positions.

$$D_H = [D_{gh} + D_{dh}(y)] - [D_t + D_r(y)] \quad (1)$$

$$D_V = [D_{gv} + D_{dv}(x)] - D_r(x) \quad (2)$$

where, D_H and D_V are the distances between the door frame and the door plate in the horizontal and vertical directions, respectively; D_{gh} and D_{gv} represent the initial gaps between the door frame and the door plate in the horizontal and vertical directions, respectively; $D_{dh}(y)$ and $D_{dv}(x)$ are the horizontal displacements caused by the deformation of the left-side jamb along the vertical direction and the vertical displacements caused by the deformation of the head jamb along the horizontal direction, respectively; D_t signifies the displacement caused by the translation of the door plate; $D_r(y)$ and $D_r(x)$ denote the horizontal and vertical displacements caused by the rotation of the door plate, respectively, and when the rotation angle, θ , is small, $D_r(y) = y\theta$ and $D_r(x) = x\theta$.

Moreover, Equations (1) and (2) can be consolidated into Equation (3).

$$D = D_{al} - D_{chg} \quad (3)$$

where, D is the distance between the door plate and the door frame; D_{al} is the allowable displacement, with $D_{al} = D_{gh} + D_{dh}(y)$ in horizontal direction and $D_{al} = D_{gv} + D_{dv}(x)$ in vertical direction; D_{chg} is the

changed displacement, with $D_{chg} = D_t + D_r(y)$ in horizontal direction and $D_{chg} = D_r(x)$ in vertical direction.

Based on Equation (3), the relationship between the door plate and the door frame at a certain location can be expressed by the following pseudocode:

if $D < 0$:

The door frame and the door plate are in compression

else if $D = 0$:

The door frame and the door plate are in contact

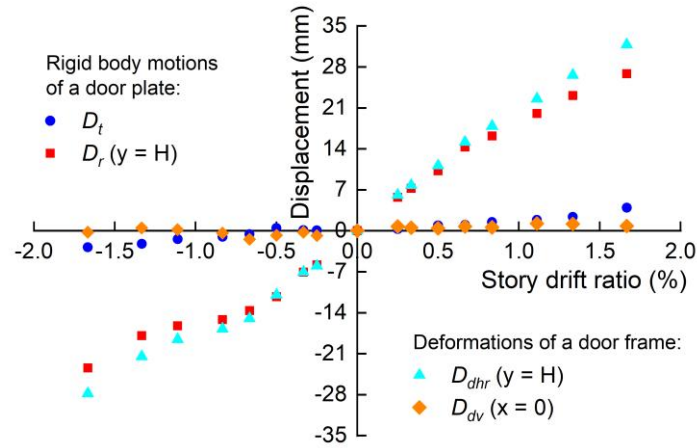
else:

The door frame and the door plate are separated

4.2 Validation of Mechanism

The data obtained from markers in Fig. 4 during the loading steps for doors are utilized to validate the mechanism. The rigid body motions of the door plate and the deformation of the door frame are expressed as $D_t = d_{x1}$; $D_r(y = H) = d_{x2} - d_{x1}$; $D_{dhr}(y = H) = d_{x5}$; $D_{dv}(x = 0) = d_{y5}$, where $D_{dhr}(y)$ is the actual deformation of the right-side jamb, as illustrated in Fig. 9. Although D_t should account for the horizontal displacement caused by rotation based on d_{x1} , it can be reasonably assumed that this displacement is negligible at the bottom due to the rotation center being located at the bottom hinge pin, which is near the M_1 , and the rotation angle is small. The non-zero values of the rigid body motion of the door plate and the deformation of the door frame, which change with increasing SDRs, indicate the existence of both the rigid body motion of the door plate and the deformation of the door frame. Thus, it is reasonable to consider the rigid body motions of the door plate and the deformation of the door frame as influencing factors in the mechanism.

306



307

308

Fig. 9. Existence of the components in the mechanism

309

310

Fig. 10 illustrates the deformation of the right-side jamb and the rigid body motion of the door plate, where

311

$D_{dhr}(y = H_1) = d_{x3}$. Due to the constraints imposed by the top hinge pin and the proximity between H and

312

H_3 , $D_{dhr}(y = H)$ is used in place of $D_{dhr}(y = H_3)$. The discrete data are interpolated into a continuous form,

313

and their goodness of fit is assessed using the coefficient of determination (COD) or Pearson's r , indicating that

314

both the deformation of the right-side jamb and the rigid body motions of the door plate exhibit a positive

315

correlation with the SDRs. The values of $D_{dhr}(y = H_1)$ and D_t are nearly identical, with a maximum

316

discrepancy of 1.09 mm, demonstrating that the deformation at the bottom of the right-side jamb controls the

317

translation of the door plate. After subtracting $D_{dhr}(y = H_1)$, the deformation of the right-side jamb at $y = H$

318

aligns closely with $D_r(y = H)$, exhibiting a maximum difference of 0.78 mm, which occurs under positive

319

SDRs. In comparison to the differences between $D_{dhr}(y = H)$ and $D_r(y = H)$ shown in Fig. 9, Fig. 10

320

demonstrates that the differential deformation between the top and bottom of the right-side jamb governs the

321

rotation of the door plate.

322

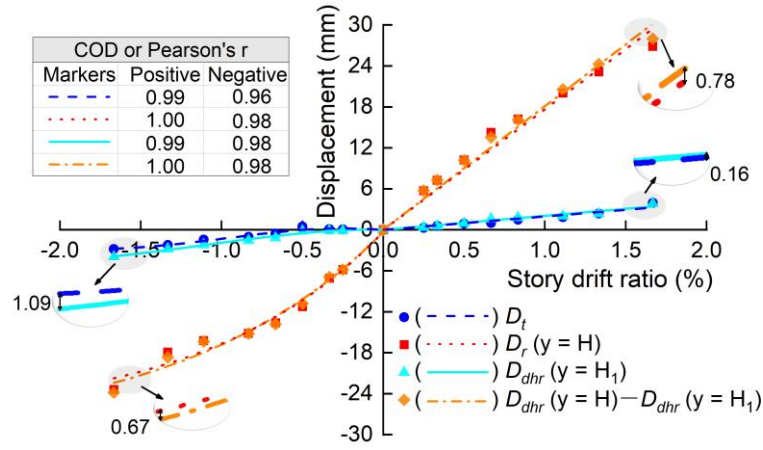


Fig. 10. Driving effect of the deformation of the right-side jamb on the rigid body motions of the door plate

The gaps at the bottom-left corner in the X direction and the top-right corner in the Y direction in Fig. 6 representatively encompass various phenomena and directions during the loading process, particularly the changes of the gap at the bottom-left corner in the X direction under negative SDRs, comprehensively representing the behavior of the door during loading. Therefore, D at the bottom-left corner in the X direction and the top-right corner in the Y direction are selected as representatives to validate the relationship between the door plate and the door frame, as shown in Fig. 11.

Since the door plate acts as a rigid body and its lower right corner does not contact the door frame, the displacement of M_1 (shown in Fig. 4) is chosen as D_{chg} , effectively reflecting the rigid body motions. D_t is identical along the vertical direction. The rotation center is located at $(0, H_1)$, resulting in $D_r(y = H_1) = 0$. Thus, for D_H , D_{chg} at $y = H_1$ is d_{x1} . Since rotation affects the displacement in the vertical direction, for D_V , $D_{chg} = d_{y1}$ at $x = 0$.

Fig. 11(a) illustrates the variation of D_H at the lower left corner, where $D_{dh}(y = H_1) = d_{x4}$. Due to the influence of construction practices, the value of D_{gh} ranges between 0 and 3 mm. Under positive loading, as the SDRs increase, D_H decreases, reaching a reduction of nearly 1 mm when the SDR is 0.5%, corresponding to step 3 in Fig. 6. A sharp decline in D_H occurs when the SDR reaches 1.33%, which aligns with step 7 in Fig.

6. However, due to the variability of D_{gh} , the gap closure occurs at different SDRs. For example, when $D_{gh} = 1.1$ mm, the gap closure occurs at an SDR of 1.33%, replicating the experimental phenomenon. Under negative loading, the reduction in D_H is 1 mm when the SDR is -0.33%, corresponding to step 2 in Fig. 6. At larger SDR values, D_H initially decreases and then increases, until it reaches a difference of less than 1 mm from the initial width when the SDR is -1.11%, which aligns with step 6 in Fig. 6. Similarly, when D_{gh} is 3 mm, gap closure does not occur.

Fig. 11(b) illustrates the variation of D_V at the top-right corner, which is influenced by D_{gv} . When the positive SDR is less than 1%, minor fluctuations are observed, until D_V decreases by more than 1 mm at an SDR of 1.11%, corresponding to step 6 in Fig. 6. As the positive SDR increases, D_V consistently decreases. Gap closure occurs when D_{gv} ranges from 0 to 3 mm, while the experimental phenomenon is replicated when D_{gv} is 5.1 mm. Under negative SDRs, D_V exhibits fluctuations but does not exceed 1 mm, consistent with the experimental phenomenon.

In summary, through the verification of the mechanism's components, the role of deformation in driving the rigid body motions, and the relationship between the door frame and the door plate, the validity of the proposed mechanism in this study has been affirmed. It is important to note that the composition of the mechanism may vary for other types of doors. For instance, rolling shutters typically feature unreinforced door plates, and thus the deformation of the door plates should be considered.

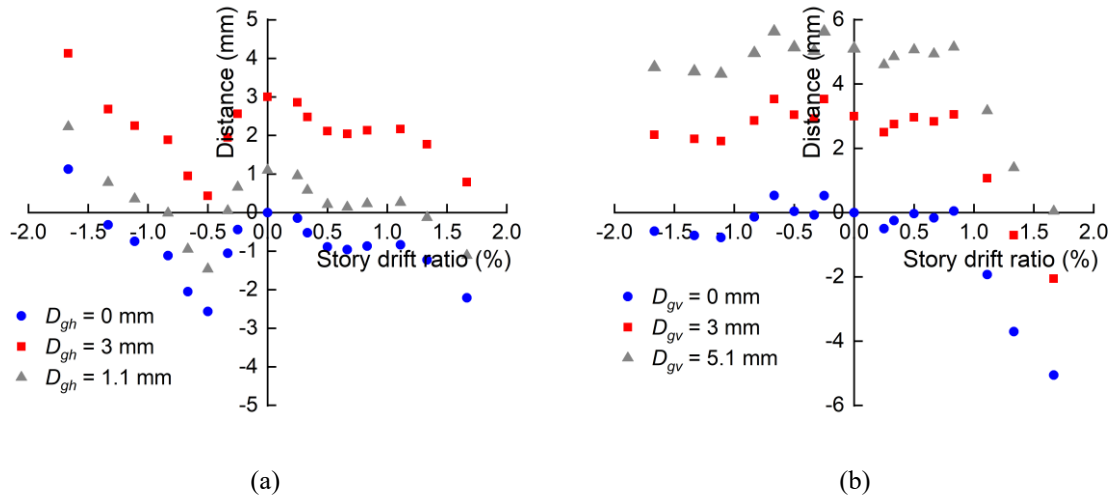


Fig. 11. Distance between the door plate and door frame: (a) Bottom-left corner in horizontal direction; (b) Top-right corner in vertical direction

5. Functional Loss

5.1 Operability States

Under the combined effects of the rigid body motion of the door plate and the deformation of the door frame, this study categorizes the operability states (OSs) of the door as OS1–OS3. OS1 indicates that the door can be manually opened; OS2 signifies that the door lock is released, yet the door cannot be manually opened; OS3 denotes that the door lock is seized.

Doors open either inward or outward, requiring pulling force and pushing force that opens the door from inside the room, respectively. Data from ISO (2007a) indicate that both pulling and pushing forces exerted by the human body are influenced by age and gender, with the pulling force being consistently less than the pushing force for the same age and gender group. To address the uncertainty in the door-opening direction, the pulling force is selected as the reference. Representing the adult working population of all ages in Central Europe, the muscle-based force limits for males and females at a working height of 1 m, which corresponds to the height of the door handle, are 259 N and 118 N, respectively (ISO 2007a). When the population is aged 50 to

64 years, the corresponding limits for males and females decrease to 201 N and 111 N, respectively (ISO 2007a). Consequently, the muscle-based force limits under pulling are utilized as the critical threshold between OS1 and OS2, constituting a range. When OS3 occurs, as the door lock is seized, pulling force is no longer a key factor in door operability and is thus not recorded.

To minimize the impact of data spikes on the critical recording of OSs, the OSs were documented between two adjacent loading steps for doors in both positive and negative directions. Under positive SDRs, the OSs at an SDR of 1.38%, corresponding to the 10th loading step for partition walls, was recorded between the 7th and 8th loading steps for doors. Under negative SDRs, the OSs at SDRs of -0.97% and -1.04% were recorded, respectively, which are between the 5th and 6th loading steps for doors.

Fig. 12 illustrates the operability states of the door. When the door requires a pulling force to be opened, there exists a linear positive correlation between the pulling force and SDRs. Under positive SDRs, OS1 persists until an SDR of 0.67%, regardless of gender. At an SDR of 0.83%, which corresponds to step 5 in Fig. 6, OS2 occurs for females, while OS1 remains for males. When the SDR reaches 1.11%, OS2 occurs for both males and females. As SDR increases, the door lock becomes seized, transitioning to OS3 at an SDR of 1.38% following step 7 in Fig. 6. By correlating with Fig. 6, the gap closure at the bottom-left corner in the Y direction increases the pulling force, triggering OS2, while gap closure in the X direction is accompanied by OS3.

Under negative SDRs, the first recorded pulling force corresponds to an SDR of -0.67%, which aligns with step 4 in Fig. 6, indicating OS1. The pulling force at step 4 is small, suggesting that the critical loading step associated with the gap closure is approaching but less than step 4, matching with step 3 (in Fig. 6). At an SDR of -0.83%, OS2 occurs for females and a portion of males, while OS1 maintains for the rest of the males. As the SDRs increase, both males and females encounter OS2. Notably, when the SDR reaches -1.11%, the pulling force exceeds 600 N and is sustained at larger values of SDRs. Throughout the negative loading process, the

door lock remains released, and OS3 does not occur. By correlating with Fig. 6, the gap closure at the top-left corner in the Y direction increases the pulling force and causes OS2, while the absence of gap closure in the X direction coincided with the non-occurrence of OS3.

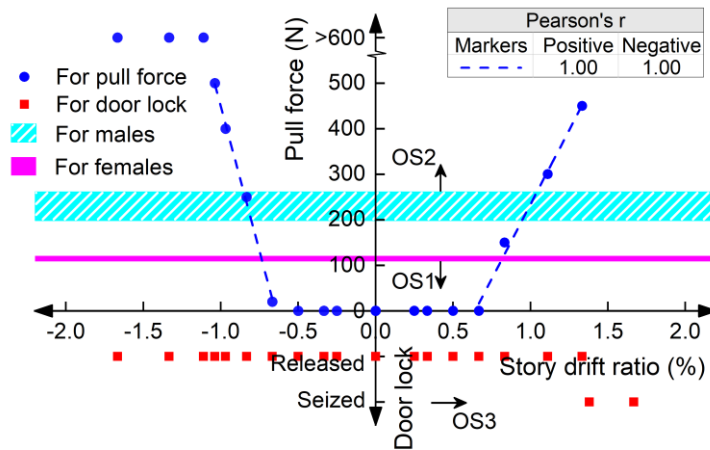


Fig. 12. Operability states (OSs) of the door

ASCE standards (ASCE 2014, 2017) specify that for Operational and Life Safety Nonstructural Performance Levels requirements, doors and connections shall be capable of accommodating SDRs of 0.5% and 1%, respectively. In Fig. 12, the door can be opened normally under both positive and negative SDRs of 0.5%, meeting the Operational requirements outlined in the ASCE Standard. However, when the SDR reaches $\pm 1\%$, OS2 is triggered, rendering the door inoperable, which compromises life safety.

5.2 Improvement Plan

To alleviate the impediments posed by doors to life safety during earthquakes, an improvement plan for doors needs to be proposed. Changes in dimensional design and layout influence the functional loss of doors to some extent. For example, increasing the height of the partition wall, which raises the height of the vertical reinforcement (L) based on the construction, can reduce deformation at certain locations of the reinforcement

under the same SDR; alternatively, placing the door at the center of the partition wall may alleviate the transmission of compression from a deformed steel frame to the door. However, dimensional design and layout are typically predetermined by engineers and owners, making modifications challenging to implement. To avoid complicating on-site construction, the connections between the door and the various components of the partition wall remain unchanged. Additionally, increasing the initial gaps and filling them with flexible materials is a potential improvement strategy; however, its implementation necessitates further validation in compliance with fire resistance requirements (AQSIQ and SAC 2008). Therefore, reducing the rigid body motions of the door plate presents an effective approach for improvement.

Through the analyses presented in Sections 4.1 and 5.1, it is determined that the occurrence of OS2 is attributable to the gap closure in the Y direction, which is controlled by the rotation of the door plate, and OS3 is observed when the gap closure occurs in the X direction, which is controlled by the translation of the door plate under positive SDRs. According to the mechanism outlined in Section 4, the rigid body motions of the door plate are driven by the deformation of the right-side jamb via the hinge pins. Specifically, the displacement of the bottom hinge pin governs the translation of the door plate, while the displacement difference between the top and bottom hinge pins governs the rotation of the door plate. Therefore, it is feasible to reduce the rigid body motions of the door plate by adjusting the height of the hinge pins to transmit varying deformations of the right-side jamb.

Since the left-side jamb and right-side jamb experience the same SDRs, the influence of the head jamb on the deformation of the right-side jamb is disregarded. Therefore, the right-side jamb and its connected reinforcement can be modeled as a two-end fixed variable-stiffness beam, without considering the effect of the door plate. The differential equation for the deflection curve is established, and the deformation of the right-side jamb is determined using boundary and continuity conditions, as expressed in Equation (4). The distinction

between $L_r(y)$ and $D_{dhr}(y)$ lies in whether the effects of the door plate are considered.

$$L_r(y) = \frac{-2y^3L(I_1I_2L - I_1I_2H + I_2^2H) + 3y^2L(I_1I_2L^2 - I_1I_2H^2 + I_2^2H^2)}{I_1^2L^4 - 4I_1(I_1 - I_2)L^3H + 6I_1(I_1 - I_2)L^2H^2 - 4I_1(I_1 - I_2)LH^3 + (I_1 - I_2)^2H^4} \times SDR \quad (4)$$

where, $L_r(y)$ is the displacement resulting from the deformation of the right-side jamb without considering the effects of the door plate, and $y \in [0, H]$; I_1 means the moment of inertia of the part comprising both the right-side jamb and its connected reinforcement; I_2 denotes the moment of inertia of the reinforcement alone.

Given that the lower end of the right-side jamb is fixed, it follows that $L_r(y = 0) = 0$. The initial height of the bottom hinge pin is set at 150 mm, which means that $L_r(y = 150)$ is L_1 in Fig. 7. Therefore, to reduce the translation of the door plate, the adjustable range for H_1 is from 0 to 150 mm. Fig. 13(a) illustrates $L_r(y = H_1)$ at an SDR of 1%, representing the displacement of the bottom hinge pin. When H_1 is 150 mm, $L_r(y = H_1)$ is smaller than $D_{dhr}(y = H_1)$ in Fig. 10, due to the neglect of the influence of the door plate. Although the variation in $L_r(y = H_1)$ is minimal, reducing H_1 can effectively decrease the translation of the door plate under large SDR conditions.

For the top hinge pin, the initial height is $H - 150$ mm, which implies that $L_r(y = H - 150)$ is L_3 in Fig. 7. Considering the center of gravity and stability of the door plate, the height of the top hinge pin should exceed $0.5H$. Therefore, $H_3 \in [0.5H, H - 150]$, with the corresponding L_r illustrated in Fig. 13(b). Reducing H_3 can effectively decrease the rotation of the door plate, thereby preventing the occurrence of OS2.

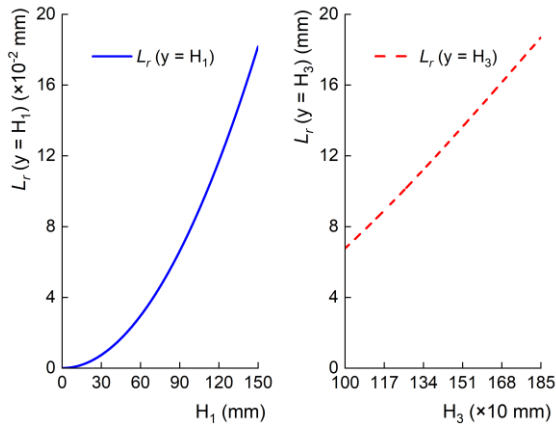
However, under negative SDRs, when the rotation of the door plate is minimal, the deformation of the left-side jamb will result in the gap closure at the top-left corner in the X direction. Since the rotation is governed by the displacement difference between the bottom and top hinge pins, the range of H_3 is influenced by H_1 . Consequently, H_3 must satisfy the condition $D \geq 0$ as expressed in Equation (3), which can be

formulated as Equation (5). It should be noted that the three terms on the right side of Equation (5) are all negative under negative SDRs.

$$D_{gh} \geq L_r(y = H_1) + \frac{L_r(y = H_3) - L_r(y = H_1)}{H_3 - H_1} H - D_{dh}(y = H) \quad (5)$$

where, $D_{dh}(y = H) = L_r(y = H)$, without considering the effects of the door plate, as the deformations of the left-side jamb and right-side jamb are similar under the same SDRs.

The right side of Equation (5) is expressed as ΔL_r , the variation of which is illustrated in Fig. 14. Taking $D_{gh} = 3$ mm as an example, the combinations of H_1 and H_3 that satisfy $\Delta L_r \leq 3$ mm can be utilized for improvement. When H_1 is 0 and 150 mm, the lower limits of H_3 are 1291 mm and 1242 mm, respectively.



(a) (b)

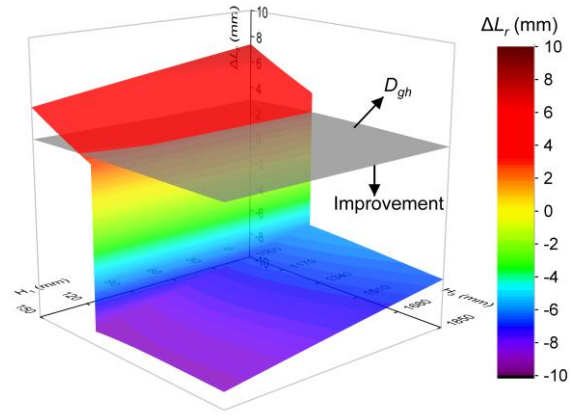


Fig. 13. Deformation of the right-side jamb without considering the effect of the door plate: (a) $y = H_1$; (b) $y = H_3$

Fig. 14. Adjustable range for the combination of H_1 and H_3

considering the effect of the door plate: (a) $y = H_1$; (b) $y = H_3$

$$y = H_3$$

5.3 Assessment of Improvement Effectiveness

To enhance life safety at an SDR of $\pm 1\%$ (ASCE 2014, 2017), where OS2 was observed during the experiment, this study adopts $H_1 = 0$ mm and $H_3 = 1500$ mm based on the improvement plan proposed in Section 5.2. The displacement difference between the bottom and top hinge pins after the improvement is expressed as $L_r(y = H_3) - L_r(y = H_1)$, disregarding the effects of the door plate.

Sections 5.1 and 5.2 demonstrate that the displacement difference between the bottom and top hinge pins is positively correlated with the pulling force required to open the door. Figures 10 and 12 illustrate the relationships between the displacement difference and SDRs, as well as the pulling force and SDRs, respectively, both of which exhibit a good fit. Consequently, the relationship between the displacement difference and the pulling force, mediated by the SDRs, is obtained, as shown in Fig. 15. However, since the fit between the pulling force and SDRs is only applicable to a specific range of SDRs, the pulling force corresponding to only a portion of the displacement differences is valid. The values of $L_r(y = 1850) - L_r(y = 150)$ are only 2.16% and 9.18% greater than the corresponding values of $D_{dhr}(y = 2000) - D_{dhr}(y = 150)$ in Fig. 10 at SDRs of 1% and -1%, respectively. Therefore, $D_{dhr}(y = 2000) - D_{dhr}(y = 150)$ is used to represent the displacement difference caused by the deformation of the right-side jamb before improvement, conservatively assessing the effectiveness of the improvement.

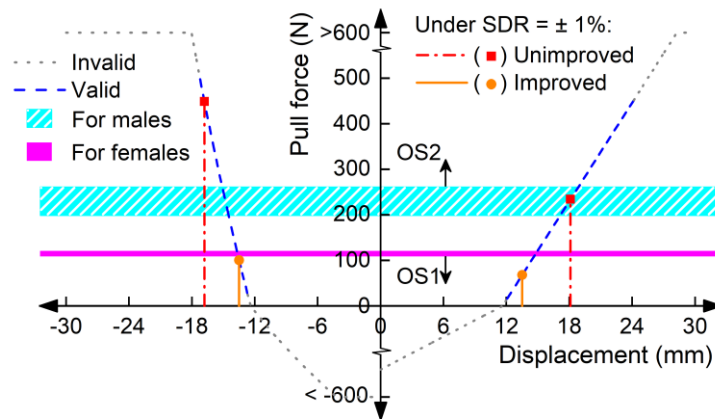


Fig. 15. Improvement effectiveness

Before the implementation of the improvement plan, the displacement difference at an SDR of 1% was 18.11 mm, resulting in the occurrence of OS2 for both females and some males; at an SDR of -1%, the displacement difference was -16.81 mm, leading to OS2 for both genders. Following the adoption of the improvement plan, the displacement difference was reduced to ± 13.50 mm, which consequently decreased the pulling forces by 71% and 78% at SDRs of 1% and -1%, respectively. As a result, OS2 transitioned to OS1, ensuring escape and rescue pathways for both females and males. Overall, the improvement plan effectively mitigated the functional loss of the door.

6. Conclusions

Through a quasi-static test conducted on a door embedded within a partition wall, the experimental results were analyzed to summarize the functional loss of doors during earthquakes from the perspectives of phenomena, mechanisms, and consequences.

The gap width between the door plate and the door frame changes under loadings. Considering the door's operability, two stages—gap reduction and gap closure—are defined based on the extent of gap narrowing. During positive loading, gap reduction occurs at the bottom-left corner and top-right corner. Based on the given initial gaps, gap closure is observed at the bottom-left corner in the horizontal and vertical directions at story drift ratios (SDRs) of 0.83% and 1.33%, respectively. Under negative loading, gap reduction occurs at the bottom-left corner and top-left corner. Gap closure occurs vertically at the top-left corner at an SDR of -0.50%, while the gap at the bottom-left corner returns to its initial width at an SDR of -1.11%.

A mechanism for the functional loss of doors is proposed and validated to explain the phenomena and provide a theoretical foundation for improvements. The displacement of the hinge pins occurs concomitantly

with the deformation of the right-side jamb. The displacement of the bottom hinge pin governs the translation of the door plate, and the differential displacement between the top and bottom hinge pins controls the rotation of the door plate. With reference to the deformation of the door frame, the vertical gaps are governed by the rotation of the door plate, whereas the horizontal gaps are influenced by both the translation and rotation of the door plate. The various gaps between the door plate and the door frame can be uniformly expressed as the distance between the two, serving as an indicator of whether they are in compression.

The functional loss of the door is expressed through three operability states: manually operable (OS1); door lock released but not manually operated (OS2); and door lock seized (OS3). OS2 occurs for females and a portion of males at an SDR value of 0.83%. OS3 is only observed under positive loading, commencing at an SDR of 1.38%. OS2 and OS3 appeared with the rotation and translation of the door plate, respectively, and can be mitigated by lowering the height of the hinge pins. The adjustable range of height was determined through the mechanism and deformation of the door frame. Following a reduction in the height, OS2 transitions to OS1 for both males and females, with the pulling force reduced by over 70% at an SDR of $\pm 1\%$, thereby achieving the Life Safety Nonstructural Performance Level.

The presented investigation is limited to a single swing steel door specimen and has not yet incorporated door typology diversity and associated uncertainties. It is hoped that this study will raise awareness among building designers and code developers regarding the seismic behavior of doors, which serve as critical passageways for escape and rescue. The findings of this study are expected to improve the construction of doors in industrial manufacturing and provide references for post-earthquake rescue efforts.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding

author upon reasonable request.

Acknowledgments

This work was supported by JSPS Kakenhi, Grant Number 21H04598 (PI: Masahiro Kurata), and JST SPRING, Grant Number JPMJSP2110.

References

ATC (Applied Technology Council). 2003. *Preliminary evaluation of methods for defining performance*. ATC 58-2. Redwood City, CA: ATC.

AQSIQ (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China), and SAC (Standardization Administration of the People's Republic of China). 2008. *Fire resistant doorsets*. [In Chinese.] GB 12955-2008. Beijing: Standards Press of China.

ASCE (American Society of Civil Engineers). 2014. *Seismic evaluation and retrofit of existing buildings*. ASCE 41-13. Reston, VA: ASCE.

ASCE (American Society of Civil Engineers). 2017. *Seismic evaluation and retrofit of existing buildings*. ASCE 41-17. Reston, VA: ASCE.

Calayir, M., S. Selamet, and Y. C. Wang. 2022. "Post-earthquake fire performance of fire door sets." *Fire Saf. J.* 130: 103589. <https://doi.org/10.1016/j.firesaf.2022.103589>.

Cook, D. T., A. B. Liel, C. B. Haselton, and M. Koliou. 2022. "A framework for operationalizing the assessment of post-earthquake functional recovery of buildings." *Earthquake Spectra* 38 (3): 1972–2007. <https://doi.org/10.1177/87552930221081538>.

FEMA (Federal Emergency Management Agency). 1997. *NEHRP guidelines for the seismic rehabilitation of*

558 *buildings*. FEMA 273. Washington, DC: FEMA.

559 FEMA (Federal Emergency Management Agency). 2007. *Interim testing protocols for determining the seismic*
560 *performance characteristics of structural and nonstructural components*. FEMA 461. Redwood City, CA:
561 FEMA.

562 FEMA (Federal Emergency Management Agency). 2018. *Next-generation Seismic Performance Assessment for*
563 *Buildings, Volume 2 - Implementation Guide*. FEMA P-58. Washington, DC: FEMA.

564 FEMA (Federal Emergency Management Agency). 2019. *Post—Disaster Building Safety Evaluation*
565 *Guidance—Report on the Current State of Practice, Including Recommendations Related to Structural and*
566 *Nonstructural Safety and Habitability* . FEMA P-2055. Washington, DC: FEMA.

567 Fujinawa, Y., and Y. Noda. 2013. Japan's earthquake early warning system on 11 March 2011: performance,
568 shortcomings, and changes. *Earthquake Spectra* 29 (1_suppl): 341–368.
569 <https://doi.org/10.1193/1.4000127>.

570 Huang, J., and M. Kurata. 2025. “Influence of Doors on the In-Plane Seismic Behavior of Partition Walls.”
571 *J. Struct. Eng.* 151 (1): 04024184.
572 <https://doi-org.kyoto-u.idm.oclc.org/10.1061/JSENDH.STENG-13618>.

573 Huang, J., M. Kurata, and S. D. Shen. 2024. “Experimental investigation and modeling of boundary
574 influences on in-plane seismic performance of partition walls.” *Earthquake Eng. Struct. Dyn.* 53 (2):
575 924–942. <https://doi.org/10.1002/eqe.4051>.

576 Huang, J., M. Kurata, Y. Kawamata, I. Kanao, L. Qi, and M. Takaoka. 2023. “In-Plane damage of partition walls
577 with various boundaries during earthquakes.” *Earthquake Eng. Struct. Dyn.* 52 (4): 1059–1077.
578 <https://doi.org/10.1002/eqe.3802>.

579 ISO (International Organization for Standardization). 2007a. *Ergonomics-Manual handling-Part 2: Pushing and*

580 *pulling*. ISO 11228-2:2007(E). Geneva: ISO.

581 ISO (International Organization for Standardization). 2007b. *Test method of doorset opening performance in*

582 *diagonal deformation - Seismic aspects*. ISO 15822:2007(E). Geneva: ISO.

583 JSA (Japanese Standards Association). 2020. *Steel furrings for wall and ceiling in buildings*. [In Japanese.] JIS

584 A 6517. Tokyo: JSA.

585 JSA (Japanese Standards Association). 2021. *Doorsets*. [In Japanese.] JIS A 4702. Tokyo: JSA.

586 Lee, T. H., M. Kato, T. Matsumiya, K. Suita, and M. Nakashima. 2007. “Seismic performance evaluation of

587 non-structural components: Drywall partitions.” *Earthquake Eng. Struct. Dyn.* 36 (3): 367–382.

588 <https://doi.org/10.1002/eqe.638>.

589 Maeda, K., Y. Masuda, and Y. Nagano. 2018. “Damage prediction of steel doors during earthquake by time

590 history analysis of buildings.” [In Japanese.] In *Proc., 2018 AIJ Kinki, Research Reports of the Kinki Branch*

591 *of the Architectural Institute of Japan. Structural Engineering*. 58: 185–188. Osaka, Japan: Kinki Branch of

592 Architectural Institute of Japan.

593 McCormick, J., Y. Matsuoka, P. Pan, and M. Nakashima. 2008. “Evaluation of non-structural partition walls and

594 suspended ceiling systems through a shake table study.” In *Proc., ASCE-SEI Structures Congress*. Reston,

595 VA: ASCE.

596 Menegon, S. J., J. Hashemi, and E. F. Gad. 2024. “Low-damage drywall partition wall system for immediate

597 post-earthquake occupancy.” In *Proc., 18th WCEE, World Conf. of Earthquake Engineering*. Milan, Italy:

598 Italian Association of Earthquake Engineering.

599 Menegon, S. J., J. Hashemi, and E. F. Gad. 2023. “Three-dimensional response evaluation of an innovative

600 low-damage drywall partition wall system for multistory buildings.” *J. Struct. Eng.* 149 (10): 04023139.

601 <https://doi.org/10.1061/JSENDH.STENG-12040>.

- Mulligan, J., T. J. Sullivan, and R. P. Dhakal. 2022. "Experimental seismic performance of partly-sliding partition walls." *J. Earthquake Eng.* 26 (3): 1630–1655. <https://doi.org/10.1080/13632469.2020.1733139>.
- Nakayachi, K., J. S. Becker, S. H. Potter, and M. Dixon. 2019. "Residents' reactions to earthquake early warnings in Japan." *Risk Analysis*. 39 (8): 1723–1740. <https://doi.org/10.1111/risa.13306>.
- NFPA (National Fire Protection Association). 2022. *Standard for fire doors and other opening protectives*. NFPA 80. Quincy, MA: NFPA.
- Pali, T., V. Macillo, M. T. Terracciano, B. Bucciero, L. Fiorino, and R. Landolfo. 2018. "In-plane quasi-static cyclic tests of nonstructural lightweight steel drywall partitions for seismic performance evaluation." *Earthquake Eng. Struct. Dyn.* 47 (6): 1566–1588. <https://doi.org/10.1002/eqe.3031>.
- Petrone, C., G. Magliulo, and G. Manfredi. 2017. "Shake table tests on standard and innovative temporary partition walls." *Earthquake Eng. Struct. Dyn.* 46 (10): 1599–1624. <https://doi.org/10.1002/eqe.2872>.
- Taghavi, S., and E. Miranda. 2003. *Response assessment of nonstructural building elements*. PEER Rep. No. 2003/05. Berkley, CA: Pacific Earthquake Engineering Research Center.
- Wang, X., T. Hutchinson, G. Hegemier, S. Gunisetty, P. Kamath, and B. J. Meacham. 2016. *Earthquake and fire performance of a mid-rise cold-formed steel framed building—test program and test results: Rapid Release Report*. Rep. No. SSRP–16/07. La Jolla, California: Department of Structural Engineering, University of California, San Diego.
- Yagi, S., J. Iyama, Y. Fukushima, T. Ishida, S. Kishiki, T. Seike, and S. Yamada. 2024. "Damage Detection in ALC Exterior Walls in Steel Structural Frames Subjected to Earthquakes Using Acceleration Sensors." *J. Earthquake Eng.* 28 (4): 1109–1126. <https://doi.org/10.1080/13632469.2023.2228928>.
- Yang, X., and S. Kishiki. 2024. "Strength of steel track-concrete slab connections in light gauge steel partition wall." In *Proc., 18th WCEE, World Conf. of Earthquake Engineering*. Milan, Italy: Italian Association of

