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ANALYSIS OF STAIRWELLS PERFORMANCE AND DAMAGE DURING WENCHUAN EARTHQUAKE

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ABSTRACT: A large number of stairwells damage took place in various buildings during the 8.0 magnitude earthquake that struck northwestern Sichuan on May 12, 2008. For these special structural elements, a post-earthquake survey was carried out in Dujiangyan and different modes of failure of the stairwells were observed. Many structural deficiencies were highlighted by the earthquake damage. It is concluded that when buildings were mainly subjected to horizontal seismic forces in the transversal direction, the types of damage of stairwells included: 1) flexural damage in staircase treads, 2) shear damage at construction interface of staircase treads (initiating at the intersection between the treads and the risers), 3) shear failure in landing beams, and 4) crushing failure in the connections between the staircase treads and the landing beams. On the other hand, when the buildings were mainly subjected to horizontal seismic forces in the longitudinal direction, the type of damage of stairwells was mainly plastic hinging in the joints of the landing beams and columns or only in the columns.

KEYWORDS: Damage, Field observation, Reinforced concrete, Stairwell, Wenchuan earthquake

1. INTRODUCTION

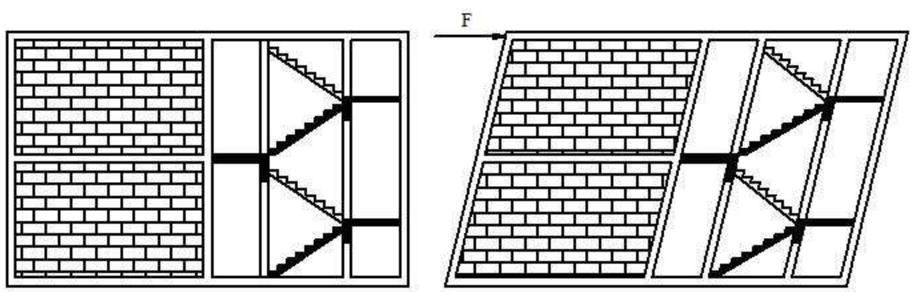
On May 12, 2008, an Mw=8.0 earthquake occurred on the 480 km-long and 100 km-wide Longmenshan fault in northwestern Sichuan. The epicenter of the earthquake was near Yingxiu, 73 km WNW of Chengdu. The location is 30.986°N, 103.364°E. Following the earthquake, a reconnaissance team was dispatched to the epicenter region to learn firsthand about the performance of the civil infrastructure. Based on the observations, damage to residential and commercial buildings was severe and widespread. The total economic loss was estimated at 86 billion US dollars. At least 69,197 people killed, 374,176 injured and 18,209 missing and presumed dead as of August 8, 2008 in the epicenter area. The majority of deaths and injuries were in Dujiangyan and Beichuan mostly caused by the collapse of buildings. This paper focuses of describing the stairwells damage of various buildings resulting from the Wenchuan earthquake, and analyzing the seismic performance of these stairwells. The performance of different types of damage in stairwells from Dujiangyan is also presented. In another paper [1], the first three authors discussed more general damages from Wenchuan earthquake observed in reinforced concrete framed buildings with and without masonry infill walls. References [2-5] present reconnaissance efforts from recent earthquakes in Turkey and Taiwan where discussions about seismic performance of main structural systems were included. However, few references about seismic performance of stairwells can be found.

2. MECHANICAL BEHAVIOR OF STAIRWELLS

According to current Chinese codes [6], earthquake action is not considered in the structural design of stairwells in all kinds of buildings, whether framed structures, masonry structures or mixed structures. The basic components of a stairwell, such as staircase treads, landing beams and platforms, are designed to support the gravity loads. It is known that the seismic response of a building is related to its orientation with respect to the direction in which earthquake waves propagate. When a building is mainly subjected to horizontal seismic forces in the transversal direction, i.e. parallel to the tread depth, stairwell mainly behaves analogous to diagonal strut, and partially prevents the building from deforming laterally. On the other hand, when a building is mainly subjected to the horizontal seismic forces in the longitudinal direction, i.e. normal to the tread depth, the joints of columns and landing beams are likely to experience damage because of the floor slab discontinuity in the stairwell reducing its overall stiffness.

2.1. Behavior of The Stairwell in The Transverse Direction

Figure 1 shows a building subjected to horizontal seismic force in the transverse direction. The staircase treads are diagonally placed on a landing beam, functioning as bracing to help resisting horizontal seismic loads. In this loading orientation and based on the observations from Wenchuan earthquake, the stairwell damages included: 1) flexural damage in staircase treads, 2) shear damage at construction interface of staircase treads (initiating at the intersection between the treads and the risers), 3) shear failure in landing beams, and 4) crushing failure in connections between the staircase treads and the landing beams.



(a) Undeformed building (b) Deformed building

Figure 1 Schematics of a transverse section elevation of a typical building

2.2. Behavior of The Stairwell in The Longitudinal Direction

When a building is mainly subjected to horizontal seismic forces in the longitudinal direction, discontinuities of floor slabs in the stairwell creates stiffness discontinuities of the whole building in the longitudinal direction due to interruption of the diaphragm action. In this loading direction and based on the observation from Wenchuan earthquake, the stairwell damage was mainly plastic hinging in the joint between the landing beam and the supporting column or only in the column.

3. PERFORMANCE OF STAIRCASES DURING WENCHUAN EARTHQUAKE

3.1. Damage Types of Staircase Treads

Figures 2 (a) to (f) show cracks occurred in the direction perpendicular to the staircase tread at middle of the staircase tread. According to the feature of damage, the cracks were caused by tension and flexure. Staircase treads were observed to experience shear damage on the construction interface initiating at the intersection between the treads and the risers where concrete was typically cast at different times, which are shown in

Figures 3 (a) to (c). One types of staircase tread damage is shown in Figure 3 (a), in which the staircase tread in the figures suffered lateral shear deformation in two perpendicular directions. The shear damage was due to insufficient shear strength in the construction interface.

The damage exerted on the staircase treads is mostly caused by horizontal seismic forces in the transverse direction. The staircase treads worked together with the landing beam and platform to brace the stairwell. Under multiple cycles of tension and compression, damage occurred in the transverse direction of the stairwell. When the strength of concrete was low due to existence of construction interfaces, the two sides of the interface tended to displace relative to each other due to interface shear forces during the earthquake. In the absence of construction interfaces in the staircase treads, tensile and flexural damages were observed.

(a) Flight side view (b) Spalling and bar buckling (c) Flexure failure

(d) Underside of a flight (e) Significant tension (f) Significant bar buckling

Figure 2 Tensile and flexural failure of staircase tread from observations after Wenchuan earthquake

(c) Shear damage (d) Complete tread failure (e) Complete tread separation

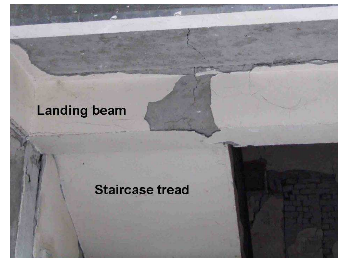
Figure 3 Shear failure of staircase tread from observations after Wenchuan earthquake

3.2. Damage of landing beams

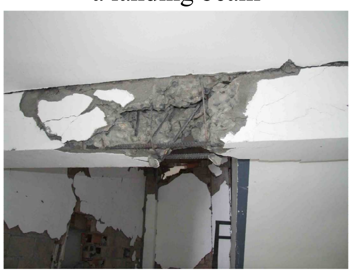
Landing beams failed in shear at their mid-span where the two flights meeting with the landing beam separate. Figure 4(a) shows a platform displaced in the horizontal direction about 6 cm during the earthquake where both the platform and the landing beam broke into two parts. Figure 4(b) shows views of a severely damaged stairwell in a masonry building which broke into two parts along the middle of the platform. One crack was observed in the platform and the landing beam in a mirror damage building in Figure 4(c). Figures 4(d) to (g) show various shear damages in the middle of the landing beams. This type of damage was widespread in the epicenter region of the Wenchuan earthquake. Shear damage with flexural deformation is shown in Figure 4(h). Finally, Figure 4(i) shows a type of landing beam spread of damage for the whole beam length due to combination of stresses.

(a) 6 cm horizontal displacement in a platform and a landing beam

(b) Landing beam spalling and cracking in a masonry building

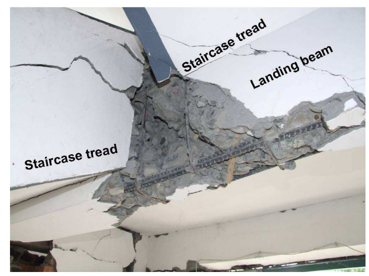


(c) Cracking in a platform and landing beam



(d) Spalling in a landing beam

(e) Cracking in a landing beam



(f) Landing beam damage at junctions with staircase treads

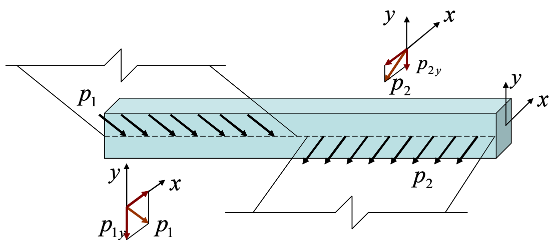
(g) Significant concrete spalling and cracking in a landing beam

(h) Shear damage and flexure deformation of a landing beam

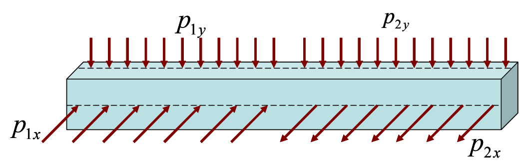
(i) Significant damage of the whole landing beam

Figure 4 Failure of landing beams observed after Wenchuan earthquake

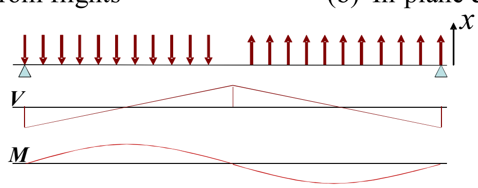
The damage in the landing beams was mostly caused by horizontal seismic forces in the transverse direction. During the earthquake, the beams were subjected to cyclic diagonal tension and compression from the staircase treads in two parts, as shown in Figure 5(a), where p_1 is the compression coming from one staircase tread, p_2 is the tension coming from the other staircase tread with p_{1x}, p_{1y} and p_{2x}, p_{2y} are the components of p_1 and p_2, in the x and y directions, respectively, Figure 5(b). Accordingly, landing beam shear force in the x direction reached the maximum value at mid-span and possibly at the ends as well, Figure 5(c), causing the observed damages after Wenchuan earthquake. Since typically the mid-span sections are designed without or with very little shear reinforcement due to action of gravity load only, earthquake damage was mostly concentrated at mid-span. In other cases, as shown in Figures 6(a) to (c), landing beams experienced a mix of shear and bending damages near their two ends during Wenchuan earthquake.



(a) Forces from flights

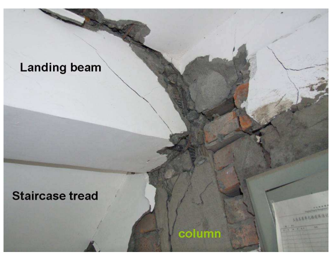


(b) In-plane & out-of-plane components



(c) Out-of-plane shear forces causing most of the damage

Figure 5 Interaction of flights and landing beam causing mid-span shear failures



(a) Shear cracks at one end

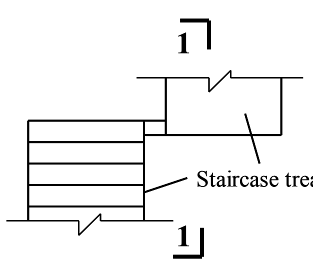
(b) Flexure and shear cracks

(c) middle and end damages

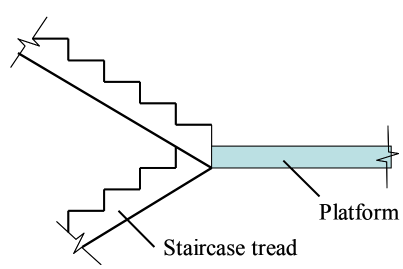
Figure 6 Shear and flexure damages near ends of landing beams observed after Wenchuan earthquake

3.3. Shear and connection damages in platform of L-shaped stairwells

Figure 7 shows an L-shaped stair slab (according to the shape in the plan view) where, in the shown case, there is no landing beam. Figures 8(a) to (c) illustrate several cases of cracking in the stair slab where the two flights meeting with the slab in L-shaped stair. Crushed concrete (mainly at the connections between the landings and the stair flights) was observed after the Wenchuan earthquake in Figures 8(d) and (e). It is to be noted that Figures 8(d) and (e) demonstrate cases of inadequate embedment length of the flight longitudinal reinforcing bars into the landing slab. Figures 8(f) to (h) show crushing of concrete in the corner of L-shaped slabs caused by the reinforcing bars developed straight.



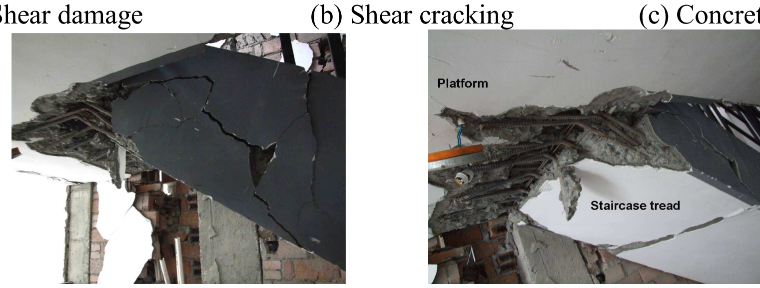
(a) Elevation view



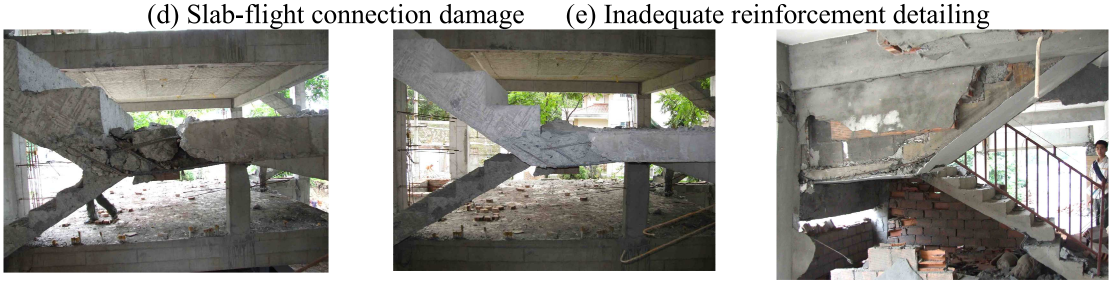
(b) View 1-1

Figure 7 L-shape stair slab

(a) Shear damage (b) Shear cracking (c) Concrete spalling



(d) Slab-flight connection damage (e) Inadequate reinforcement detailing

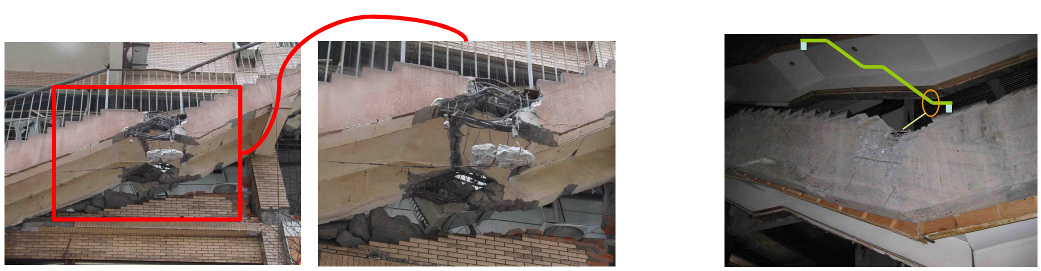


(f) Concrete crushing (g) Concrete spalling (h) Significant damage

Figure 8 Damage of L-shaped stair slabs observed after Wenchuan earthquake

3.4. Damage in The Inclined Beams of Z -shaped Stairwells

Having a landing in between two flights is required for large story heights characterizing the class of Z-shaped stairwell (according to the shape in the elevation view). Figure 9 illustrates two levels of damages (severe and moderate) to the inclined beams and slabs in Z-shaped stairwells observed after the Wenchuan earthquake. The damage was concentrated in the corner of the inclined beams due to tension and compression components produced by the earthquake loading.



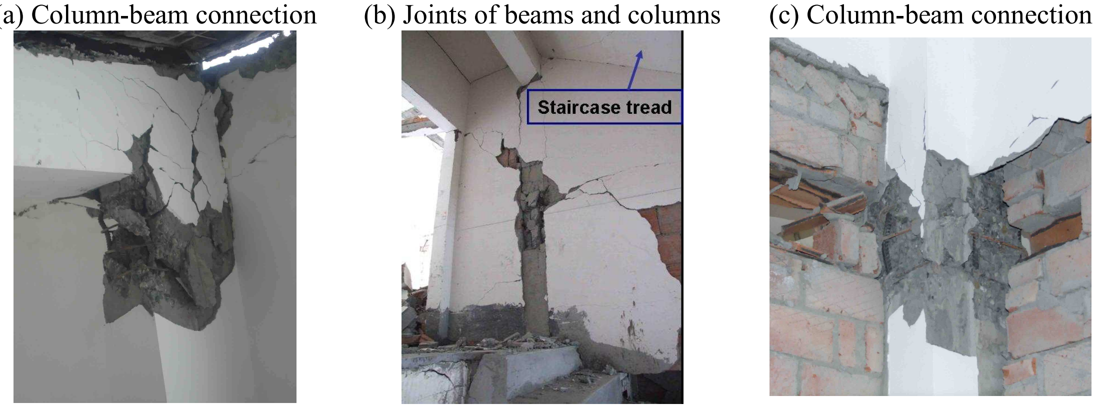
(a) Collapse of inclined beam and slab (severe damage) (b) Moderate joint damage

Figure 9 Damage of inclined beam in Z-shaped stairwells in Dujiangyan

4. DAMAGE TO MAIN STRUCTURE ARROUND STAIRWELLS

The plastic hinging in the columns which support the landing beams in Figure 10 were observed by the reconnaissance team after the Wenchuan earthquake. In general, the columns around the stairwell were damaged more severely than columns in other parts of the building, especially in RC framed buildings. This is indicative of the large seismic lateral forces attracted to these columns by the stiffening effects of the stairwell. The damage of the main structure around the stairwell was caused by the horizontal seismic forces in the longitudinal direction caused by ground shaking component in that direction. The discontinuity in the floor slabs due to the existence of the stairwell reduces the overall stiffness in the longitudinal direction due to reduction of the diaphragm action. Therefore, damage takes place in the main structural elements as observed in the different cases shown in Figure 10.

(a) Column-beam connection (b) Joints of beams and columns (c) Column-beam connection



(e) Plastic hinging (f) Column in infilled frame (g) Plastic hinging in the middle

Figure 10 Damages in columns of main structure around stairwells in Dujiangyan

6. CONCLUDING REMARKS

Wenchuan earthquake reconnaissance effort resulted in the observations of many forms of building damages ranging from moderate to severe. Focusing on the performance of stairwells, the following general conclusions can be inferred:

(A) The types of damage when a building was mainly subjected to horizontal seismic forces in the transverse direction (parallel to tread depth) were: (1) flexural damage in staircase treads, (2) shear damage at construction interface of staircase treads (initiating at the intersection between the treads and the risers), (3) shear failure in landing beams, and (4) crushing in joints between staircase treads and landing beams.

(B) The type of damage when a building was mainly subjected to horizontal seismic forces in the longitudinal direction (normal to tread depth) was mainly plastic hinging in the joints of the landing beams and columns or only in the columns.

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