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Preliminary investigation of seismic damage to two steel space structures during the 2013 Lushan earthquake

Dai Junwu[†], Qu Zhe[‡], Zhang Chenxiao[§] and Weng Xuran[§]

Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, CEA, Harbin 150080, China

Abstract: Severe damage to steel space structures is rarely reported when compared to other structural systems damaged during past major earthquakes around the world. Two gymnasiums of steel space structures in downtown Lushan County that were damaged during the 2013 *M*7.0 Lushan earthquake in China were investigated and the observations are summarized in this paper. Typical damage to these two steel space structures ranges from moderate to severe. Moderate damage includes global buckling and dislocation of bolted connections of truss members, and inelastic elongation of anchor bolts and sliding of pedestal plates of supports. Severe damage includes member fracture caused by local buckling, and fracture failure of anchor bolts and welds. The distribution of structural damage to these two structures is described in detail and future research opportunities are suggested.

Keywords: Lushan earthquake; steel space structure; gymnasium; seismic damage; member buckling; fracture failure

1 Introduction

An *M*7.0 earthquake occurred in Lushan, an area located in the southwestern Sichuan Province on April 20, 2013. The earthquake resulted in 193 deaths, 25 people missing and 12,211 injured. During the emergency inspection immediately after the earthquake and a more detailed reconnaissance three weeks later, severe damage was observed in two gymnasiums, which were both steel space structures located in downtown Lushan County. They are the first steel space structures to be heavily damaged by earthquake ground motions in China.

Downtown Lushan is a small town with a population of about 120,000 located about 17 km southwest of the epicenter of the earthquake. Two strong ground motion stations, namely LSF and YAM, maintained by the China Strong Motion Networks Center (CSMNC, 2013), are located within 20 km of downtown Lushan. The recorded peak ground accelerations were 420.1 cm/s^2 and 375.8 cm/s^2, respectively. According to the officially released intensity map (CEA, 2013), in downtown Lushan, the borders area of Intensity IX, buildings and houses without seismic design could be seriously damaged during the earthquake.

2 Brief description of damage

2.1 Structure A: Lushan Middle School gymnasium with double layer grid roof

The Lushan Middle School gymnasium is a two-story reinforced concrete (RC) moment-resisting frame building that was designed and constructed after the 2008 *M*8.0 Wenchuan earthquake, with financial support from Macao. Its first story was occupied as a café and its second story was a gymnasium that included a basketball field. The roofing system is a double layer steel grid structure (denoted as Structure A, hereafter) resting on eighteen supports on top of the RC columns (Fig. 1). The double layer grid is composed solely of square pyramids. The bolted spherical bearing at each support is welded to a cruciform steel stand with a base plate fastened to a steel plate embedded in the top of the RC column by four φ24 anchor bolts. The top layer of the grid was covered by profiled steel sheets, which were heavily damaged during the earthquake and had been removed at the time of inspection about three weeks after the earthquake. Primarily as a result of the loss of the roof, the occupancy of the building was suspended after the earthquake, although the RC frame structure remained essentially intact. In addition, Structure A sustained severe seismic damage including global buckling (Fig. 2(a)) and dislocation of truss members

Correspondence to: Dai Junwu, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, CEA, Harbin 150080 China
Tel/Fax: +86-451-86652883
E-mail: junwudai@126.com
[†]Professor; [‡]Associate Professor; [§]PhD Student

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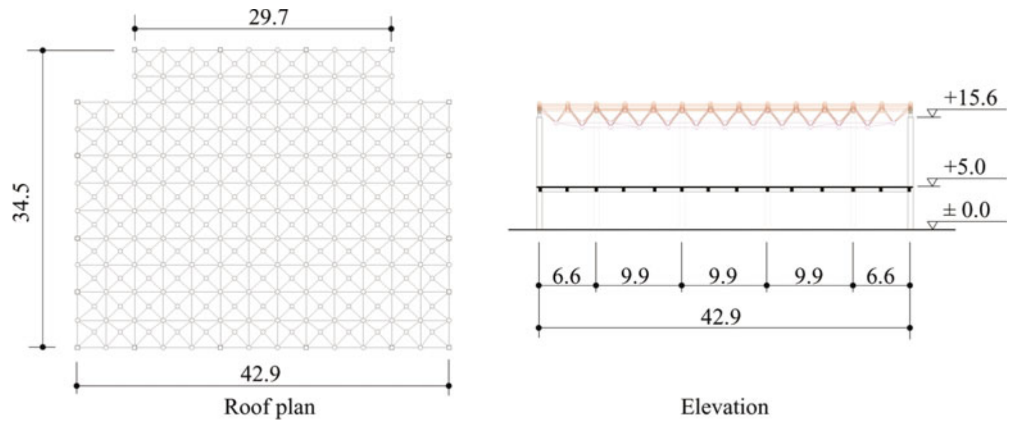

Fig. 1 Structural layout (left) and profile (right) of the Lushan Middle School gymnasium (length unit: m)

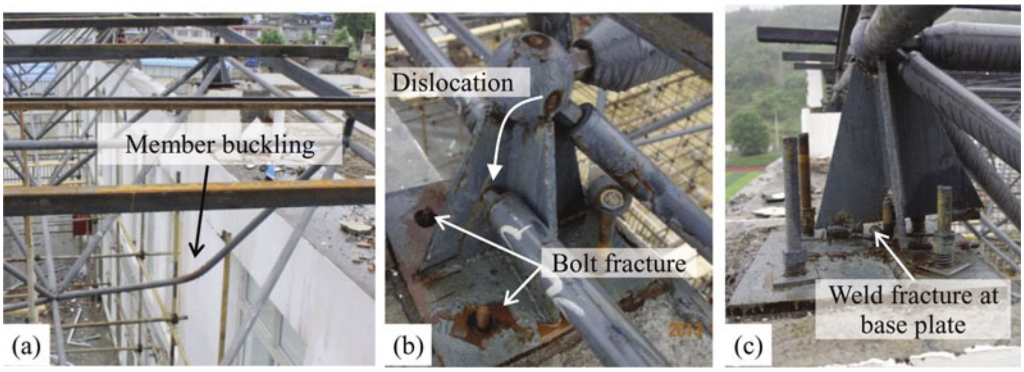

Fig. 2 Typical damage to truss members in Structure A

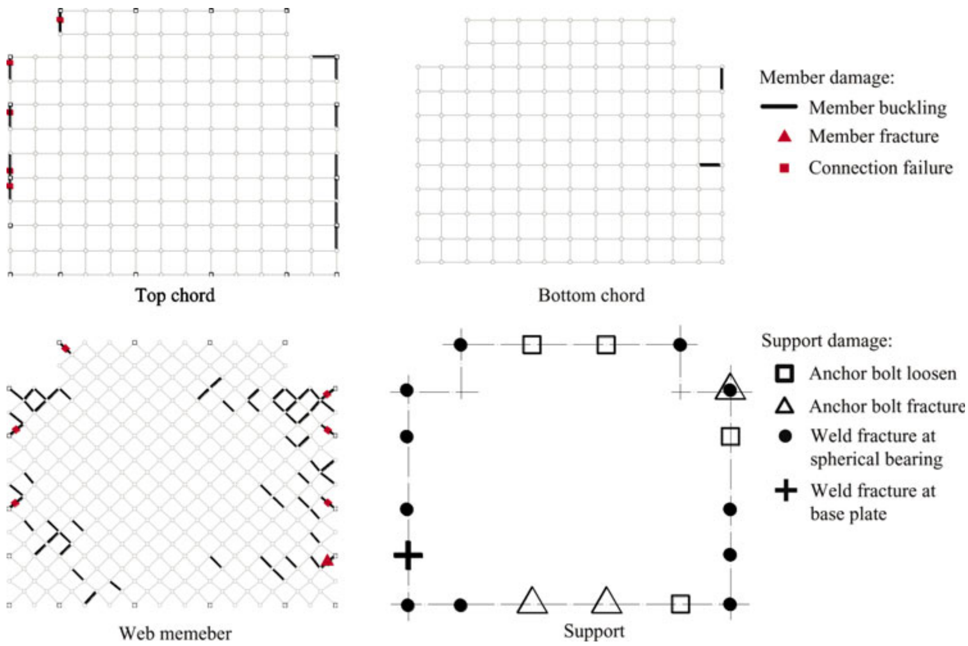

Fig. 3 Damage distribution observed at four different levels of Structure A

(Fig. 2(b)), fractures of the anchor bolts at the base plates (Fig. 2(b)) and weld fractures of the support (Fig. 2(c)).

Figure 3 depicts the distribution of observed damage to the truss members as well as to the supports. As with the truss members, web members seemed to be more vulnerable to either tensile or compressive damage than the chord members. In particular, six of the web members that were connected to the supports sustained both global buckling and connection failure, indicating significant tensile and compressive load reversals during the earthquake. The buckling of these web members, which should remain in tension under gravity load, indicates that vertical ground motions may have lifted the steel grid up, subjecting them to significant compression.

All eighteen supports sustained various damages and twelve of them failed because of weld fracture. Most fractured at the spherical bearing while one fractured at the weld between the base plate and the cruciform steel stand, which should have been much stronger than at the spherical bearing (Fig. 2(c)). Such unexpected damage may be attributed to poor quality control of the welding.

2.2 Structure B: Lushan Gymnasium with double layer lattice shell

Like Structure A, the Lushan Gymnasium was constructed after the 2008 Wenchuan earthquake as part of the reconstruction efforts in the earthquake affected area. The steel structure of the gymnasium is composed of a double layer lattice shell, which can be considered as a combination of an inclined dome and an arch (Fig. 4). Both the dome and the arch are primarily composed of square pyramid units. Tetrahedral units are also used in some transition zones. The lattice shell covers an ellipse-shaped indoor space of 69.0 m wide and 72.5 m long and is supported at different elevations on rubber cushions on top of 22 RC columns around the perimeter of the gymnasium and nine supports on the ground at each of the two abutments of the arch.

Similar to Structure A, typical damage to the truss members in Structure B include global buckling (Fig. 5(a)), steel fracture (Fig. 5(b)) and failure of bolted connection at spherical nodes (Fig. 5(c)). The seismic damage to the supports of Structure B were not as severe as to Structure A. Slight loosening and offset of the anchor bolts were observed on 19 of the 22 supports on top of the RC columns, while inelastic elongation and fracture of the anchor bars were found on two of the nine supports on the ground.

Figure 6 shows a distribution of the observed seismic damage on the space roof structure and its supports. Visual inspections identified damage to 131 truss members in the steel lattice structure, including 17 top chords, 36 bottom chords, 70 web members and eight supporting struts. In addition, some moderately or severely damaged members that were difficult to see may have been missed during the inspection. The damage to the fixed based arch was generally more significant than to the dome, which rests on flexible rubber supports. The joint zone of the dome and the arch seems more vulnerable to seismic effects than other parts of the lattice shell. The most severe damage to the truss members was observed on a supporting strut located at a corner where the arch meets the dome as indicated by a solid triangle in Fig. 6. The fractured strut is 3,202 mm long and is

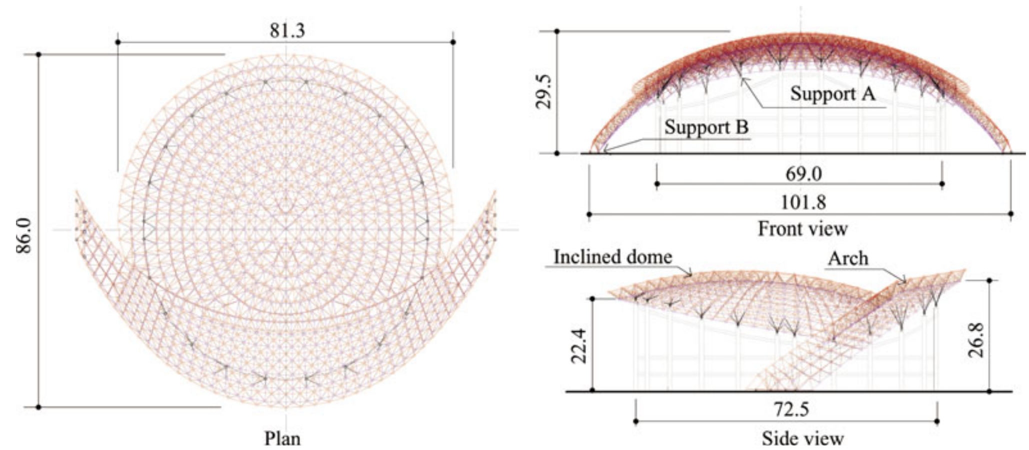

Fig. 4 Structural layout and profiles of Lushan Gymnasium Structure B (length unit: m)

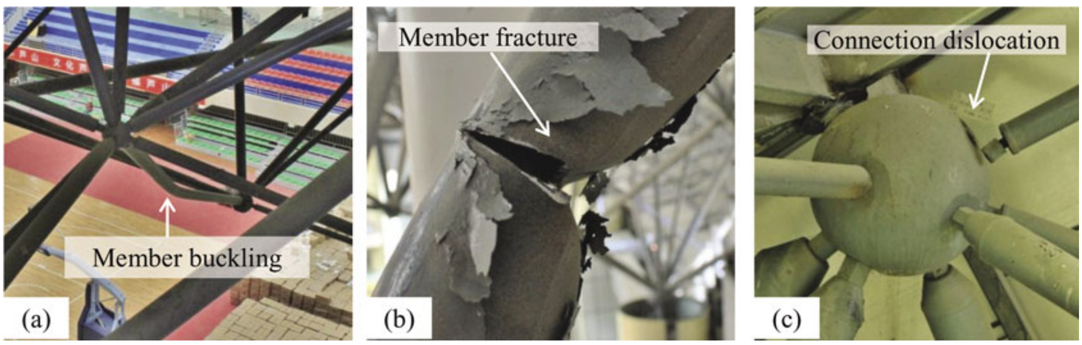

Fig. 5 Typical damage to truss members in the lattice shell structure of Structure B

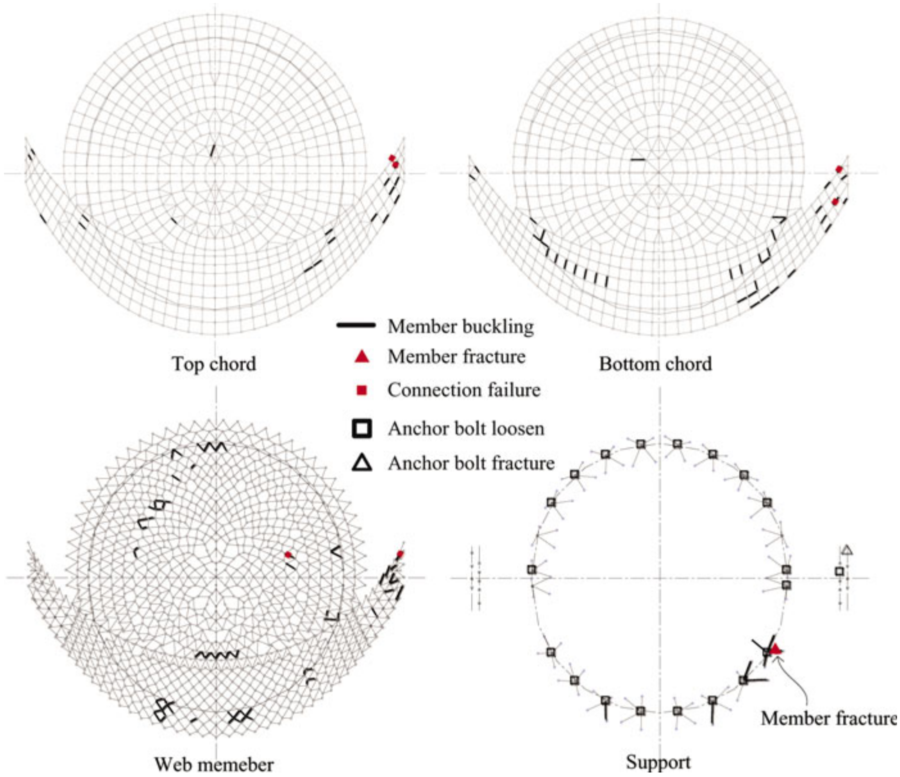

Fig. 6 Observed seismic damage distribution of steel lattice shell of Structure B

made of steel tubing 114 mm in diameter and 4 mm in thickness. Three hinges formed because of steel fracture at both ends and in the middle of the strut (Fig. 5(b)). Note that the support to which the fractured strut was welded is located on top of a three-story masonry-infilled RC frame building attached to the inside of the gymnasium. The large lateral stiffness of the attached building very likely caused force to be concentrated on the supports on top of the building, and thus exacerbated local damage to the struts that were there.

3 Summary

An investigation of seismic damage to the steel space structures of two gymnasiums located in downtown Lushan during the 2013 *M*7.0 Lushan earthquake was carried out during the days immediately following the earthquake and followed by a more detailed reconnaissance three weeks later. The observations, which are believed to be the first time severe seismic damage to this type of structural system has been seen, are described in this paper. The observations are expected to encourage further studies to better understand the seismic behavior and damage mechanisms of steel space structures. The following topics are identified for further research.

(1) Seismic demands from vertical ground motions for space steel structures similar to Structure A. These demands may not have been properly addressed in the seismic design, where the steel structure roof and the RC frame underneath were analyzed independently as per common practice in China.

(2) Higher mode vibration characteristics of irregular steel space structures in both horizontal and vertical directions as observed in Structure B. The special shape as well as the mixed use of flexible and fixed supports may have had a major impact on the global dynamic behavior of these structures.

(3) Effects of steel construction quality control on the seismic performance of steel space structures.

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