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Experimental study on progressive collapse-resistant behavior of planar trusses

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ABSTRACT

This paper presents an experimental study on the dynamic progressive collapse behavior of planar trusses. A specially designed member-breaking device has been invented to 'break' a predefined structural member suddenly, particularly a diagonal member in the experiments. Videogrammetric technique was adopted to obtain the full field 3D displacement of the remaining structure, and strain instrumentation was carefully used to monitor the internal forces of all members. In association with the experiments, finite-element simulations of the test trusses have also been performed, with extended analysis on the effect of removal of members at different locations. Experimental results in conjunction with the numerical analysis have shown that: (1) the truss with directly welded joints (specimen truss-WJ) was able to quickly regain balance upon member loss, and the load-redistributing capacity was provided mainly through catenary action developed in the bottom chord; (2) the truss with pinned joints (truss-PJ) behaved almost identically to truss-WJ, suggesting that when computational models of truss structures need to be developed to obtain structural responses under a collapse scenario, pinned-joints with continuous chord could be assumed; (3) the truss with rigid joints (truss-RJ) experienced progressive buckling of three diagonal members and was damaged severely, indicating a detrimental influence of excessive joint stiffness on the collapse resistance of trusses.

1. Introduction

Building structures may be subjected to man-made (by accident or act of terrorism) or natural hazards, causing local failure such as loss of one or more load-carrying members. As a result, a progressive collapse of the entire structure may be triggered. American Society of Civil Engineers (ASCE) Standard 7 defines progressive collapse as "the spread of an initial local failure from element to element resulting eventually in the collapse of an entire structure or a disproportionately large part of it" [1].

Since the destruction of the Alfred P. Murrah Federal Building in 1995 [2] and the collapse of the World Trade Center towers in 2001 [3], the engineering community, including codes and standards development organizations, public regulatory agencies and research institutions, has been paying significant attention to the performance of buildings subjected to damage from abnormal events. A large number of studies have been conducted, including experimental studies [4–8] and numerical investigations [9–13]. Based on these studies, structural robustness assessment methods have been proposed [14–19], and codes and guidelines for design against progressive collapse of structures have also been released or updated [1,20–23]. However, up to date, most of the studies have focused on the collapse resistance mechanism of frame structures, whereas relevant information on space structures, especially on large-span roofing systems, is very limited. Space structures can have a number of types and forms, and the load-carrying mechanisms rely heavily on the structural shapes. This is very different from frame structures, and thus the potential collapse resistance mechanism of the space structures can be different from that of the frame structures. The rule of the key members which may be 'removed' due to the accidental load can also be different between normal building frames and space structures. Moreover, space structures are usually constructed as important public buildings capable of accommodating a large number of people. Collapse of these structures will cause significant casualties and substantial property losses. Hence, the progressive collapse mechanism of space structures is also an important subject, and considering the

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sparse data currently available, there is an urgent demand for studies on this front.

Truss is one of the most commonly used forms of large-span roofing systems. Available studies on progressive collapse performance of this type of space structures were mainly carried out employing the Alternate Path Method, in which a load-bearing element was instantaneously removed to evaluate the general integrity of a structure and its capacity in redistributing the loads following severe local damage. Studies conducted by Murtha-Smith et al. [24], Malla et al. [25] and Jiang et al. [26] have shown that although truss structures usually have a large degree of redundancy, progressive collapse could occur following the loss of one of the critical members. However, all of the above studies were conducted through finite-element analysis, whereas experimental studies were few. Physical tests are necessary to directly reflect the nonlinear behavior of space structures in collapse scenarios and provide benchmark data for the validation of finite-element models.

In practical engineering applications of tubular trusses or traditional trusses constructed from profile steel members, partially rigid joints (e.g. by welding) are usually adopted. But when a calculation model needs to be developed to obtain the structural response, engineers often assume idealized pinned or rigid joints, as shown in Fig. 1, instead of considering the partial-rigid characteristic of the truss joint because the latter is more computationally expensive. The adequacy of the idealizations for progressive collapse design should also be examined from the structural analysis point of view. In a pinned-joint model, the chords may be treated as discontinuous at joints (see Fig. 1(a)) when there is no external load over the chord members or otherwise continuous (see Fig. 1 (b)). However, when analyzing a progressive collapse scenario, the pinned-joint model with a discontinuous chord would not be appropriate in any case because it overlooks the resistance provided by the bending moment in the actual continuous chord and thus underestimates the collapse resistance of the overall structure. An idealization with rigid joints and/or pinned joints with continuous chord may need to be adopted in a progressive collapse analysis of truss structures with welded joints, but the extent to which such modelling idealization may affect the accuracy of the analysis need to be evaluated based on experimental evidences.

This paper presents a comprehensive experimental study on the dynamic progressive collapse resistance of planar trusses, which constitute a basic form of large-span space trusses. Three reduced-size planar Warren trusses have been tested under a sudden loss (removal) of a diagonal member. The three tested trusses had the same geometric and material properties but different types of joints, and they were subjected to identical applied loading conditions. The first truss (referred as specimen truss-WJ) was a typical tubular truss with welded joints. The other two trusses, referred as specimen truss-PJ and truss-RJ, had specially-designed joint connectors which enabled the diagonal members to connect to the continuous chords in perfectly pinned (-PJ) or rigid (-RJ) fashion, respectively. By comparing the three cases, the collapse resisting mechanisms of the practical welded-joint truss can be revealed, and the influence of the joint stiffness on the progressive collapse resistance of a truss structure can also be studied.

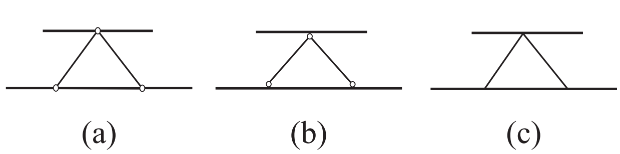

Fig. 1. Simplified joint assumption in truss model. (a) Pinned joint with discontinuous chord; (b) pinned joint with continuous chord; (c) rigid joint.

Furthermore, the experiment and the associated analysis contribute to establishing a library of benchmark models of space structural systems for future numerical and parametric studies.

2. Test program

2.1. Specimens

Three tested trusses were carefully prepared and tested. The first specimen, truss-WJ, was a typical planar Warren truss with directly-welded joints and was designed according to Chinese Code for design of steel structures (GB50017) [27]. As shown in Fig. 2, the truss had a span of 4.0 m and a height of 0.45 m. The top chord (TC), bottom chord (BC) and diagonal members (DM) were constructed using DIN2391 St.35 steel pipes. The cross-sections and mechanical properties are shown in Table 1. The diagonal members were directly welded to the top and bottom chords. The two edge supports (SJ1 and SJ2) were made as fixed pins with full horizontal restraints. It should be noted that in practice the horizontal stiffness provided by the supports may vary depending on specific construction detailing. Using fixed-pin supports without horizontal degree of freedom were adopted to represent an upper bound pinned-support condition for the trusses. Recognizing that different behavior may be observed if the horizontal restraining conditions are changed, this effect may need further studies, but this is not within the scope of this study.

The second and the third specimens, i.e. truss-PJ and truss-RJ, had the same geometric and material properties as those of truss-WJ; but instead of using directly welded joints in truss-WJ, specially designed pinned joint connectors and rigid joint connectors were adopted for Truss-PJ and truss-RJ, respectively, as shown in Fig. 3. The pinned joint connector (see Fig. 3(a)) was comprised of four precisely machined parts:

a: a top steel block whose bottom was machined with a half-cylinder groove with the same diameter as the chord member;
b: a bottom steel block whose top was machined with an identical half-cylinder groove and bottom was machined with a lug plate;
c: two steel sleeves with ear plates on top; and
d: two pins that connected the steel sleeves to the lug plate of bottom steel block.

When truss-PJ was constructed, the chords were clamped by the steel blocks through welding and bolts, and each diagonal member was extended into the steel sleeve with welding at the interface. In this way, each diagonal member was connected to the chord allowing free rotation around the pin, i.e. the in-plane rotational degree of freedom was released. For truss-RJ, the rigid joint connector (see Fig. 3(b)) was similar to the pinned joint connector except that there was no lug plate in the bottom steel block, nor ear plates existed in the steel sleeve; the steel sleeve was directly welded to the bottom surface of the bottom steel block. The welding was sufficiently strong such that no relative translational and rotational movement was allowed between the steel

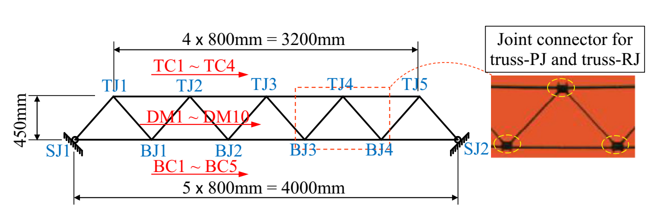

Fig. 2. Overview of the tested trusses.