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Original Research Article

Collapse mechanism analysis of a steel moment frame based on structural vulnerability theory

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ABSTRACT

This paper presents an improved method to analyze the collapse mechanism of steel moment frames based on structural vulnerability theory (SVT), in which the failure processes of the essential components are defined according to the damage characteristics of their ductile and brittle members. The improved method can accurately identify possible collapse modes of steel moment frames, because the transformation processes of such connections as beam-column joints and support joints from rigid connections to pinned ones were considered. Structural vulnerability analysis is performed on a 4-story steel frame structure by using the improved method, the results show that the collapse caused by joint failure in the first story had the maximum vulnerability index, so that the weakness of the steel frame may be located in the first story; while the collapse behaving as a ''beam plastic hinge'' failure, as an expected failure mode, had the minimum value. Moreover, the improved method was validated by a shaking table test due to the consistence between the experimental results and the collapse modes calculated to have the maximum vulnerability index, which demonstrates that such improved method could be effectively to predict the collapse modes of steel frame structures.

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1. Introduction

Robustness is recognized as an essential aspect of the safety of a structure, it is adopted that a robust-designed structure has the enough ability to resist damages and avoid disproportionately large consequences caused by minor damage [1]. However, robustness has not yet been considered in a uniform assessment system [2,3]. Vulnerability is another aspect that can reveal the sensitivity of structures to damaging events and reflect the corresponding bearing capacities, which resulting in the indirect characterization of the robustness.

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Structural vulnerability theory (SVT) is an method to identify the weakness of a structure, and the vulnerability index was used to quantify the inherent vulnerability of the analyzed structure. The vulnerability index can be calculated according to the consequence generated from initial damage and the requisite damage demand [4,5]. Two typical analyzing processes including clustering and unzipping processes were derived in SVT to identify the possible failure scenarios of building structures [6,7]. According to the identified failure scenarios, the weakness of the structure can be found. Based on the SVT, various types of failure modes were identified in two traditional Portuguese buildings with timber construction [8]. The applicability of the SVT was verified by comparing with the actual failure modes according to the tests. Such SVT method were also used in three reticulated K6 domes with single-layer by Ye and his colleges [9–11], it was found that the predicted collapse modes with the highest vulnerability index based on the SVT were similar with the shaking table test results. Such results demonstrated that the SVT could be used to predict the collapse modes of space structures. In addition, SVT method were used to predicted the potential failure modes of cold-formed steel shear walls (CFSW) [12], and it was found that this theory can be applied to CFSW structures. Such approach defined collapse based on the significant disproportion size in the initial and final damage configuration was also proposed by Starossek [13] and Brunesi et al. [14]. The traditional SVT is used by choosing a component as a basic element, thus the identified failure modes are comprised by a collection of components. However, plastic hinges formed at the end of the components and failure of joints are the commonly happened failure modes of the steel frame structures due to earthquakes [15], therefore the traditional SVT could not identify some possible failure modes of steel frame structures.

Steel frame structures often have a high density of inhabitants, as it is a structural system that is extensively used in residential and commercial buildings. During an accidental external action such as an earthquake, disastrous consequences would be generated if the local or even total collapse of the structures occurred. For steel moment frames, studies on their collapse mechanisms have usually been realized by shaking table tests [16,17]. Seismic experiments and corresponding numerical analyses on 4-story steel moment frames were conducted to validate and predict their collapse modes [18–27]. The joints of the first story were concluded to be the weakness of the structure, thus panel walls were commonly used to enhance the resistance of steel frames [28,29]. However, experiments and complex numerical analysis on full-scale steel frame structures are costly and time-consuming, thus a simplified theory-based method may be more attractive.

Therefore, this paper developed an efficient method to reveal the collapse mechanism of steel frames, and to overcome the boundedness of the traditional SVT. The connection transformation process from rigid joints to pinned ones was considered in this method on the basis of the mechanical features of steel moment frames and the actual experimental response of components. Finally, this improved method was used in a 4-story steel frame structure to analyze the collapse mechanism of the structure.

2. Traditional SVT

SVT is focusing on both the internal structural form and connectivity of a structure, is an analytical method to probe the inherent weakness of a structure on the basis of the connections between components. The theory analyzes the inherent relation of the structure from a point of stiffness and quantitatively evaluates the effects of external actions.

2.1. *Structural rings and clusters*

A structural ring is a basic unit of a structural cluster, and a structure can be consisted by one or several structural clusters. Fig. 1 shows a structural ring comprised by three components, this structural ring can turn into a mechanism once a component failed, as shown in Fig. 1. A structural cluster can be divided as following.

(a) Initial structural cluster is a component which is used to form a structural ring.
(b) Leaf cluster is a structural cluster comprised by several components.
(c) Reference cluster is usually the ground, a structure is defined as total failure if the structure is separated from the reference cluster.

2.2. *Well-formedness*

Well-formedness is an important indicator for the connecting effects of each element at a joint. The well-formedness of joint *i* can be calculated as [3–7]:

$$q_i = \det(\mathbf{D}_{ii}) = \lambda_1 \times \lambda_2 \times \lambda_3 \tag{1}$$

where λ_1, λ_2 and λ_3 represent the load-bearing capacities in the eigenvectors directions for each joint and are named the principal stiffness coefficients of joint *i*, the values of which are relative to the stiffness and relative position as well as the connection type of each element. Among them, λ_1 and λ_2 are the stiffness coefficients associated with translational directions, while λ_3 is the rotational one; for pinned joints, λ_3 is vacant.

Given that the joint number of a structure is *n*, the well-formedness is then defined as an average value of all joints:

$$Q = \sum_{i=1}^{n} \frac{q_i}{n} \tag{2}$$

The physical meaning of the well-formedness can be concluded: total buckling behavior of structures and components, moment distribution of beam and column components

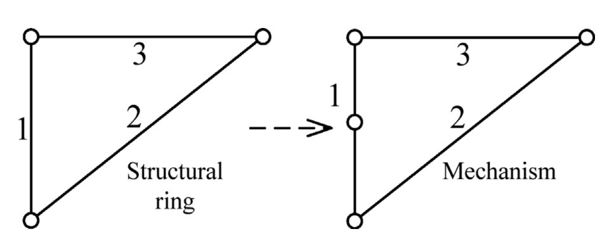

Fig. 1 – A structural ring and its failure expression.

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