Thin-Walled Structures 123 (2018) 70–81

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Analysis of the progressive collapse of space truss structures during earthquakes based on a physical theory hysteretic model

Hua-Dong Zheng, Jian Fan*

College of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Keywords:
Physical model
Bar element
Failure criterion
Explicit dynamic analysis
Seismic collapse

ABSTRACT

This study develops a force–displacement hysteresis model (computer program) for a bar element based on a physical theory model. The model is capable of capturing complex physical phenomena of member, such as yielding under tension, non-elastic buckling under compression, growth effect and degradation of buckling capacity due to the Bauschinger effect. The proposed element model is validated by comparing the simulation results with previous experimental results and is applied to the dynamic analysis of space truss structures. The explicit dynamic analysis method is adopted for solving the nonlinear equations of motion. Furthermore, a case study of a three-layer space truss structure is conducted. The reliability of the proposed algorithm and the need to develop the bar element are verified by comparing the results obtained using the proposed method and the ANSYS finite element analysis software package. Moreover, several fracture criteria for bar elements are defined and are used to analyse the progressive collapse of a space truss structure under seismic loading. The analytical results demonstrate that the selection of the fracture criterion for the bar members significantly affects the calculation of the collapse of the space truss structure under seismic loading. The strut buckling/softening-based fracture criterion can be used to relatively accurately evaluate the collapse resistance of a space truss structure under seismic loading. Finally, the collapse mode of a power transmission tower model under seismic loading is simulated. The simulation results are then compared with the collapse mode of a power transmission tower with a similar structure that collapsed during the Wenchuan earthquake. The simulation results agree closely with the observations, thereby verifying the reliability of the proposed algorithm.

1. Introduction

A structure undergoes progressive collapse when failure occurs in one part of the structure under irregular loading (e.g., a strong earthquake, impact, blast or fire), resulting in initial damage and, in turn, leading to a redistribution of the internal stresses of the structure. This subsequently causes failure in other parts of the structure, which eventually precipitates the structure to partially or completely collapse [1]. Truss structures are extensively used in bridges, ocean platforms, power transmission towers and long-span roof trusses. Because truss structures are highly sensitive, the failure of a key bar member of a truss structure will generally lead to the collapse of the entire structure. In 1978, several struts of the space truss roof of the Hartford Civic Center Coliseum (Hartford, USA) started to buckle under a heavy snowfall; the failure developed rapidly, and the entire roof collapsed instantaneously [2]. In addition, numerous large power transmission towers have collapsed during earthquakes. For example, 20 power transmission towers became tilted as a result of the 1995 Kobe earthquake [3], 15 power transmission towers collapsed, 26 power transmission towers were tilted due to the 1999 Chi-Chi earthquake [4], and more than 20 power transmission towers underwent progressive collapse during the 2008 Wenchuan earthquake [5], resulting in tremendous economic losses. Therefore, the calculation and analysis of the progressive collapse of truss structures caused by strong earthquakes are of significant value to engineering practice.

In recent years, several researchers have studied the collapse characteristics of truss structures. By subjecting a space truss roof system to various types of loading until failure, Fülöp et al. [6] studied the stability and ductility of this structure and obtained the moment–rotation curves of the structural joints. Malla and Nalluri [7] calculated the dynamic response of a space truss structure after the sudden failure of one member and concluded that the failure of the key bar member of a structure will result in changes in the mode, frequency and displacement of the structure and is extremely likely to lead to the instantaneous collapse of the entire structure. Hanaor et al. [8] studied a collapsed steel truss bridge through experiments and theoretical

---

* Corresponding author.
E-mail address: fan-jian@hust.edu.cn (J. Fan).

https://doi.org/10.1016/j.tws.2017.10.051
Received 1 May 2017; Received in revised form 28 October 2017; Accepted 31 October 2017

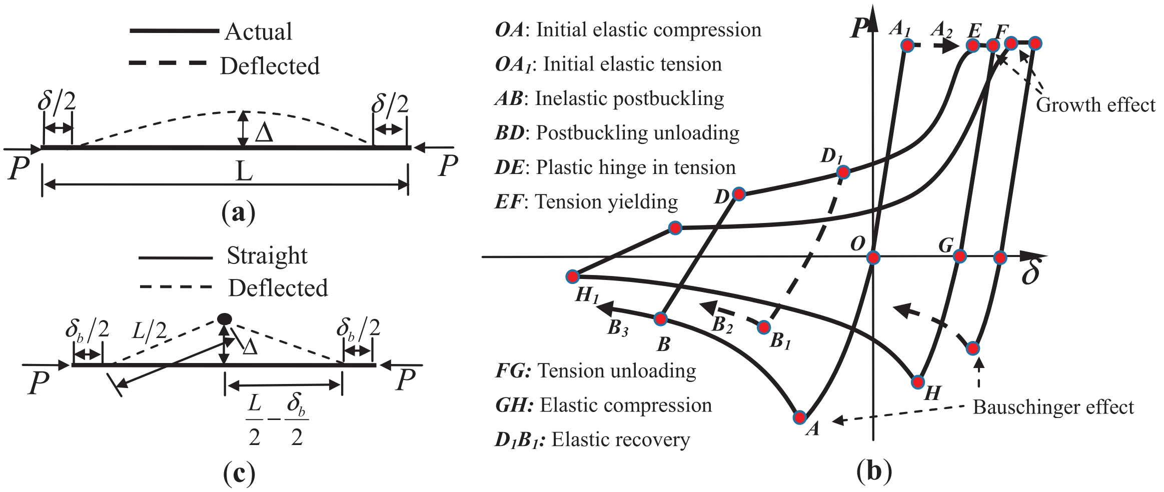

Fig. 1. (a) Compressive deformation of a bar element; (b) the hysteretic loop, growth effect and Bauschinger effect; (c) relationship between the axial and longitudinal displacements.

numerical simulations and found that when the stiffnesses at the ends of the members of a structure are insufficient, the stable load-carrying capacity of the members or even the entire structure are dramatically reduced. Yu et al. [9] simulated the collapse of a cantilever space truss structure under typhoon conditions using a finite particle method and determined the collapse mechanism of the structure. They also compared the simulation results with field observations to verify the practicality of the finite particle method. Power transmission towers are typical truss structures, and their collapse will incur large economic losses. Therefore, several researchers have conducted extensive research on power transmission towers. Wang et al. [10] simulated the progressive collapse process of a power transmission tower under seismic loading by varying the ultimate strain (ε_{crit}) of the material using ABAQUS and found that the collapse resistance of the structure increases significantly as ε_{crit} increases. By simulating the collapse of a power transmission tower system under multi-component seismic excitations using ABAQUS, Tian et al. [5] studied the collapse path, failure mode and collapse resistance of the structure. Eslamlou et al. [11] analysed the nonlinear dynamic progressive collapse of a power transmission tower based on the OpenSees program and evaluated the key bar members of the structure. Their results showed that the OpenSees program can effectively predict the behaviour of the key bar members of power transmission towers. Albermani et al. [12] developed a nonlinear finite element program to analyse the collapse of power transmission towers under static horizontal loading, which was validated by comparing the calculation results from the proposed program with full-scale test results.

The force-displacement hysteresis behaviour of the bar members is the key to accurately predict the collapse resistance of the space truss structure. Under reciprocating loading, behaviour of slender bar members involves complex physical phenomena, such as yielding under tension, non-elastic buckling under compression, growth effect and degradation of buckling capacity due to the Bauschinger effect. When a bar member undergo buckling and softening under compression, its stiffness and load capacity will suddenly decrease, resulting in the redistribution of the internal forces between other bar members. In the process will produce dynamic effects which easily lead to structural collapse. The stiffness and strength of the bar member will also gradually recover in the subsequence tension process, but the critical buckling load show a significant reduction due to Bauschinger effect in the next compression process. Currently, there are three methods which can be used to predict the hysteresis behaviour of bar members: the three-dimensional finite-element method (FEM) [13–16], the physical theory model method [17–19], and the phenomenological model method [20,21]. The FEM has highly fidelity but takes a lot of computing time. A phenomenological model gives an explicit expression of stress-strain relationship, which can efficiently simulate the nonlinear behaviour of bar members. However, some parameters in the model need to be calibrated by numerous experimental data. A physical theory model is based on fundamental physical behaviour which can develop a plastic hinge at midspan. The model cannot capture some aspects of localized behaviour, but it can simulate overall axial force-displacement response reasonably [22].

The studies presented above demonstrate that there are still several problems with the simulation of the collapse of space truss structures. Common finite element software packages, such as ABAQUS and LS-DYNA, are typical analytical tools used to simulate the seismic collapse of truss structures. However, these finite element software packages have no ready bar elements that simulate compression member buckling and softening [5,10,11]. While a low cycle fatigue sensitive material model of Uriz and Mahin [23] was implemented in the computer analysis framework OpenSees that can simulate the buckling and softening behaviour of members, the total number of elements used to represent each member was 24, and 64 fibers were used to represent each square HSS and round HSS [24]. In this study, the physical model proposed by Dicleli et al. [18] is used to simulate the buckling and softening behaviour with only one element per member. In addition, the effects of fracture failure of members are considered and the explicit dynamic analysis method is employed to develop a computer program for simulating the progressive collapse of truss structures under seismic loading.

2. Hysteresis model for bar members

The physical model proposed by Dicleli et al. [18] is used to simulate the buckling and softening behaviour of bar members under compression. This model can consider the complex physical phenomena associated with the hysteretic behaviour of a thin and long space bar element. Fig. 1(a) shows the compressive deformation of a bar member, and Fig. 1(b) shows the axial load (P)–axial displacement (δ) hysteretic loop of the Dicleli et al. model. The physical hysteretic behaviour of a bar member can be expressed using $\boldsymbol{P}$, δ and the lateral displacement at the midspan (Δ).

In the physical model of Dicleli et al. (Fig. 1(a)), δ is composed of the following two parts:

$$\delta(t) = \delta_e(t) + \delta_{in}(t) \tag{1}$$

where δ_e represents the elastic axial displacement, and δ_{in} represents the axial nonlinear displacement. The component δ_e can be expressed as follows: