Engineering Structures 50 (2013) 1–12

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Elasto-plastic analysis based truss optimization using Genetic Algorithm

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ARTICLE INFO

Article history:
Available online 3 January 2013

Keywords:
Elasto-plastic analysis
Truss optimization
Genetic Algorithm
Multi-objective optimization
Collapse load factor

ABSTRACT

In this paper, the incremental elasto-plastic analysis method, is utilized to predict the collapse load factor of truss structures. The obtained collapse load factor is then incorporated into truss optimization using a Genetic Algorithm (GA) in order to generate truss structures which cannot only maintain load-carrying capacity under ordinary load conditions, but also avoid collapse under accidental load conditions such as an extremely large earthquake. Our designed optimization scheme is successfully implemented to solve two optimization problems, indicating the successful realization of designed optimization scheme.
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1. Introduction

The Genetic Algorithm, based on the Darwinian survival-of-the fittest theory, is an efficient and broadly applicable global search algorithm because it works directly with solutions instead of the derivate information [1]. Since Adeli and Cheng [2] presented optimization of space structures by integrating GA with the penalty function method, a number of papers have been published on structural optimization using Genetic Algorithms in the literature. Research has been carried out in recent decades focusing on either the improvement of the optimization method of GA [3–6] or the speeding up of the optimization process through advanced computers [7–9]. On the other hand, there are also a number of studies [10–12] focusing only on truss structural optimization problems and some of them have contributed to practical truss optimization [13,14].

Our review of the literature indicates no article with respect to truss optimization taking into account the ultimate load-carrying ability of the truss structure. According to the design procedure in Japan, structural design usually consists of two design stages. In the first design stage, structures must be able to keep their load-carrying capacity under ordinary load conditions such as dead load and live load. In the second design stage, structures ought to have sufficient resistance to some accidental load conditions such as extremely large earthquakes and drastic typhoons. As a rule, in the first design stage, stresses of structural members calculated via the Finite Element Method (FEM) must be limited to the allowable stress required by related design criteria. Next, during the second design stage, structures undergo plastic analysis to predict their ultimate load-carrying ability, which is often evaluated by the collapse load factor [15]. With the guarantee of the collapse load factor being larger than the load factor of an accidental loading, engineers can ensure the structure's safety under accidental load cases. The incremental elasto-plastic method [15] is conventionally used for the calculation of the collapse load factor of a frame structure. In this study, we use it to calculate the collapse load factor of truss structures under a few assumptions.

Based on the authors' earlier study [13], by adding the ratio of the collapse load factor to the load factor of an accidental load as a constraint to the truss optimization using GA, this paper attempts to present a truss optimization problem with consideration of both the first and second design stages.

2. Incremental elasto-plastic analysis method and structural calculation

2.1. Application to truss structure

The incremental elasto-plastic analysis method is based on the plastic hinge concept for fully plastic cross sections in a structure under increasing proportional loading in a frame structure. It assumes that a plastic hinge would occur if the bending moment at a section reaches the plastic moment, and will maintain that the value with the bending moment increases in other sections until the whole structure becomes a collapse mechanism.

However, for truss structures, there are no bending moments in structural components, only axial forces. Based on the assumption of steel being an elastic-perfectly-plastic material, to simulate the plastic hinge in frames, we assume that a 'plastic hinge' happens in a truss structure when a member bearing tension force reaches yield stress, or a member bearing compressive stress reaches buckling force. Similarly, like the plastic hinge in a frame structure, we

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http://dx.doi.org/10.1016/j.engstruct.2013.01.010

also assume that those members have reached yield stress or buckling stress will maintain their ultimate stress value as axial forces increase in other members until the whole truss structure collapses. As such, the incremental elasto-plastic analysis method can be used to calculate the collapse load factor of truss structures. A typical example of calculation of the collapse load factor of truss structures is shown in Fig. 1, which is compared to the collapse process of a frame structure.

The process of calculating the collapse load factor of truss structures is summarized as follows:

Step 1: For a truss bearing an accidental loading P_a, the normalized loading of P_a, denoted as P_0, is first applied to the structure (Fig. 1-i).
Step 2: Gradually increase P until the first set of elements collapses and indicate the new P with $\lambda_1 P_0$ at this moment (Fig. 1-ii).
Step 3: If the structure does not become a mechanism after step 2, continue increasing P till a new set of elements collapses. Denote the new P by $(\lambda_1 + \lambda_2)P_0$. Note that, during this step, the increased stresses of non-collapsed elements are obtained by calculating a new structure, having no elements collapse in the former step, under the loading $\lambda_2 P_0$, and the stress of the collapsed member in the former step does not vary again.
Step 4: Repeat step 3 until the structure becomes a collapse mechanism, and denote the final P by $(\lambda_1 + \lambda_2 + \cdots \lambda_n)P_0$ (Fig. 1-iv). As a result, the collapse load factor of the truss structure is

$$\lambda_{cr} = \sum_{i=1}^{n} \lambda_i \tag{1}$$

where n is the number of iterations to become a mechanism. The load factor of accidental load is

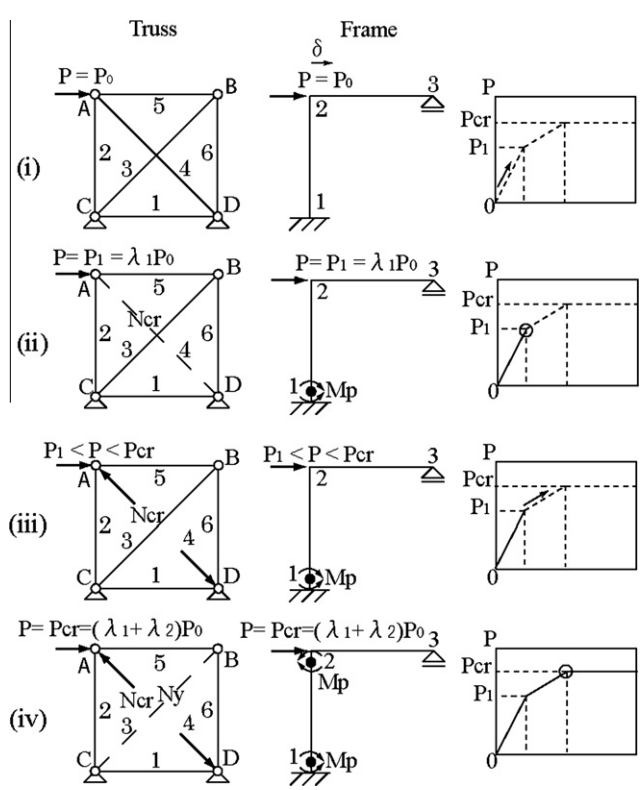

Fig. 1. Incremental analysis method for truss.

$$\lambda_a = P_a / P_0 \tag{2}$$

If λ_{cr} is larger than λ_a, the structure is considered safe under the accidental loading P_a.

Thus, structural calculation considering both the first and second design stages in current study can be demonstrated in Fig. 2.

2.2. Post-buckling influence

In the above section, the incremental elasto-plastic analysis method is applied to truss structures based on the assumption that truss structural members can maintain their buckling stresses until the overall collapse of the structure. However, it is shown in the literature that the axial stress after buckling may decrease if the axial strain continues increasing [16]. Fig. 3 shows the experimental behavior of post-buckling, in which N_c is the external compression axial force and N_y is the yield force. Therefore, it is necessary to investigate the influence of post-buckling on the collapse load when the incremental elasto-plastic analysis method is applied to truss structures.

In our study, the commercial software MIDAS/Gen 7.30 is used to investigate this influence. Basically, in MIDAS/Gen 7.30, there are two types of plastic hinges available for elasto-plastic analysis of truss structures; one is named bilinear type hinge, and the other is named FEMA type hinge. The definition of their load–displacement curve is shown in Figs. 4 and 5, respectively, in which users need to input the yield and buckling strength values for each truss member. It is easy to learn that the bilinear hinge type is the same as our assumption, while the FEMA type is able to consider the axial force reduction after buckling. However, a diagonal definition of the line between $-b$ and $-c$ in Fig. 5 is impossible in MIDAS, which causes a difficulty in simulating the progressively reducing phenomenon in post-buckling (shown in Fig. 3). For this reason, we proposed a new method to solve this problem, in which we bind together a group of n elements with FEMA hinge to simulate one truss member and give these elements different values at $-b$ and $-c$ (each line connecting points $-ci, -bi, -a, a$, and b $(1 \leqslant i \leqslant n)$ in Fig. 6). As a result, these elements will buckle one by one as external force increases, resulting in a progressive reduction in the total axial force of these elements (line connecting points $-C, -B, -A, B$, and C in Fig. 6). Suppose the cross-sectional area of original truss member is A_0, those elements have to satisfy the following conditions:

(1) The total cross-sectional area, yield and buckling forces of these elements must be equal to those of the original truss member (Eqs. (3a)–(3c)):

$$\sum_{i=1}^{n} A_i = A_0 \tag{3a}$$

$$\sum_{i=1}^{n} N_{yi} = N_{y0} \tag{3b}$$

$$\sum_{i=1}^{n} N_{cri} = N_{cr0} \tag{3c}$$

where A_0 is the cross-sectional area of original truss member; N_{y0} is the yield force of original truss member; N_{cr0} is the buckling force of original truss member; n is the number of elements used for simulation; A_i is the cross-sectional area of element i; N_{yi} is the input yield force of element i; and N_{cri} is the input buckling force of element i .

(2) The yield and buckling forces input for those elements are calculated through the following equations (Eqs. (3d)–(3f)):

$$N_{yi} = f_y A_i \tag{3d}$$

$$N_{cri} = \frac{A_i N_{cr0}}{A_0} \tag{3e}$$

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