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Seismic collapse prediction of frame structures by means of genetic algorithms

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ABSTRACT

This paper presents an automatic approach for the evaluation of the plastic loads and failure modes of planar frames. The method, based on the generation of elementary collapse mechanisms and on their linear combination aimed at minimizing the collapse load factor, is here originally extended to account for the contemporary presence of permanent and incremental loads. The presence of permanent distributed loads acting on beams, which affects the occurrence and the location of along-axis plastic hinges, is here evaluated by means of an exact formulation. Each elementary mechanism is built and studied through an original code developed in the agent-based programming language NetLogo, which is here employed for the first time with structural engineering purposes. The developed software interface is very user-friendly and has a great versatility. The minimization procedure is efficiently performed by means of genetic algorithms, which allow to compute both the collapse load factor and the correspondent failure mode with great accuracy and in a very short computing time. The possibility of taking into account both incremental horizontal load distributions at each floor level and permanent vertical loads on beams provides, for the first time, an automatic method which allows to obtain fast and reliable information on the resistance and collapse mechanisms of frame structures subjected to seismic loads. Many applications have been performed, either with reference to the classical plastic analysis approach, in which all the loads increase proportionally, or with seismic load scenarios. In the latter case, the numerical results have been compared to those obtained with pushover analysis, showing, in a shorter computing time, a very good correspondence even for large structures. Finally, a parametric study has also been performed, aiming at evaluating the influence of some geometric, mechanical and load distribution parameters on the ultimate collapse load of planar frames subjected to seismic loads.

1. Introduction

The problem of plastic analysis and design of frame structures has been deeply analysed by many researchers since the middle of the past century [1] by means of two different approaches. The first of these is the finite element method in which the global stiffness matrix of the system is computed and the response of the structure is obtained solving iteratively a set of non linear equations [2]. In this analysis the history of loading is applied incrementally until the failure of the structure, therefore the analysis can be very time-consuming.

The method proposed in the manuscript is based on limit analysis which provides information on the carrying capacity and collapse mechanism of structures. Limit analysis is a reliable method, and is faster with respect to nonlinear static and dynamic analyses; for this reason it is still widely employed by practitioners. It is directly based on the kinematic theorem of limit analysis; by analysing all the possible collapse mechanisms of a structure and the related collapse loads, the correct ultimate load is determined seeking the absolute lowest value among the considered mechanisms. This method therefore does not require the direct computation of the stiffness matrix and it is not necessary to apply the complete history of loading.

Many contributions can be found in the literature aiming at solving plastic collapse problems for example by means of linear programming [3–5] or at the optimal plastic design of beams [6] or frames considering as constraint the minimum weight of the structure [7–10] or a generic cost function of design variables [11].

In the limit analysis kinematic approach, one of the most frequently used method is that first developed by Neal and Symonds

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[8,9] in which only the elementary mechanisms are analysed and these are combined to obtain a final collapse mechanism whose load factor is the lowest of all the possible combinations. The mechanism associated to the lowest load factor represents the actual failure mechanism of the structure.

In the literature significant contributions to the automatic computation of the mechanisms for limit analysis of frames have been provided by Watwood [10], Gorman [11], Deeks [12] and Kaveh [13].

The main limitation of plastic analysis and design of frames using a combination of elementary mechanisms is the tedious work of combining them to find the true collapse mechanism. Since both steps of generating the elementary mechanisms and combining them are time-consuming, it is therefore important to develop a methodology capable of finding an approximate collapse load factor and the corresponding mechanism as fast and accurate as possible. To this purpose, very interesting approaches may be found in heuristic algorithms based on natural computation, which have the capability to converge on a good solution independently of the specific search space to which they are applied [14,15]. Among them, genetic algorithms have been often employed for engineering purposes when a functional to be maximized can be defined and when the configuration of the system is particularly suitable to be described by means of arrays of integer numbers, which represent the "chromosomes" [16,17]. In particular, in the field of structural engineering, they have been mainly adopted for design purposes [18] and inverse problems [19,20]. Kaveh et al. [21–23] and Kohama et al. [24] presented studies on the determination of collapse load factors of planar frames by means of genetic algorithms. Kaveh and Jahanshahi studied the plastic limit analysis of frames using heuristic algorithms and ant colony systems [25–28]. A comparison between the performance of co-evolutionary and genetic algorithms in the optimal design of structures has been presented by Hofmeyer et al. [29]. Rafiq proposed a structured genetic algorithm for the optimum design of buildings [30]. A combined parametric modelling and genetic algorithm for performance-oriented process in structural design has been proposed by Turrin et al. [31]. Aminian et al. developed a hybrid genetic and simulated annealing method for estimating base shear of plane structures [32] and also studied the collapse of castellated beams [33]. More recently, Jahanshahi et al. [34] proposed a comparative study on the determination of collapse load of planar frames by means of neural networks, genetic and ant colony algorithms, while Kaveh et al. have performed plastic analyses of planar frames by means of either colliding bodies optimization or its enhanced version [35,36].

The present work focuses on the strategy of seeking the collapse load by means of genetic algorithms. With reference to frame structures, elementary collapse mechanisms method was already employed by several authors, also in combination with genetic algorithms. On the other hand, the presence of permanent loads, crucial for the assessment of the seismic capacity of frame structures was never investigated and automatic procedures to account for such an aspect were never proposed. The presence of permanent loads on beams affects the location of plastic hinges when an incremental horizontal load distribution is considered; for this reason when their contribution is neglected coarse errors in the seismic collapse prediction of frame structures may occur. In this study for the first time an automatic method based on limit analysis able to provide fast and reliable information on the resistance and collapse mechanisms of frame structures subjected to seismic loads is proposed. The main novelties of the paper consist of the possibility of developing a seismic analysis in which only the horizontal forces are incremented while permanent vertical loads remain constant, and of the new way of approaching the automatic computation of elementary collapse mechanisms of planar frames, based on a regular grid, by means of an original software code in the agent-based programming language NetLogo [37]. This software environment has been usually adopted by many researchers to simulate complex systems dynamics in several different fields, but, at the authors' knowledge, never to structural engineering. In this context, the original developed code allows building into a virtual metrical space and visualizing in the user interface every single mechanism and the correspondent collapse load by means of a very user-friendly approach and can be therefore used even from non expert operators and for educational purposes. Successively, in a very small computing time, the elementary mechanisms are combined and the minimum collapse load is obtained by means of an optimization procedure based on genetic algorithms. The peculiar aspects of the application of genetic algorithms to collapse mechanisms have been described in the paper together with the fundamentals of NetLogo's logic.

Several applications have been performed both with reference to the classical plastic analysis approach, in which all the loads increase proportionally, and with a seismic point of view considering a system of horizontal forces whose magnitude increases while the vertical loads are assumed to be constant.

While the aim of the first applications is mainly to validate the proposed approach by comparison with some of the available results provided in the literature and to study the performance of genetic algorithms, the seismic applications represent an original contribution towards the limit behaviour of structures under earthquake excitations.

In case of seismic analysis the plastic hinges may occur at the two ends of the columns and, due to permanent vertical loads, also in any section along the beam. For this reason a correct location of the plastic hinges along the beam is required as proposed by Mazzolani et al. [38].

In the present paper, the values of the collapse load, obtained by means of the proposed method for seismic applications, have been compared to the correspondent results provided by nonlinear push over analysis showing a very good correspondence. The computing time related to the two above mentioned procedures has been compared for increasing size of the considered frame, allowing to show the great advantage of the proposed procedure.

Furthermore, an extensive parametric study has been performed aiming at evaluating the influence of some geometric and mechanical parameters, of the intensity of permanent vertical weights, and of the shape of the horizontal force distribution on the ultimate collapse load of planar frames.

The achieved results, with reference to the parametric studies, not only may provide significant information on the seismic performance of frame structures, but also represent a useful tool in their optimal design. In fact, although the presented results refer to some specific structures, general trends in the seismic behaviour of planar frames can be deduced.

2. Combination of elementary mechanisms and collapse load

In the present study planar regular frames are considered. These are characterized by the number of floors N_f and the number of columns N_c.

The columns at the ground level are assumed to be clamped, therefore the degree of hyperstaticity of the structure, denoted by h, is:

$$h = 3[N_c - 1 + (N_f - 1)(N_c - 1)] \quad (1)$$