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Original Research Article

Characterization of the cyclic-plastic behaviour of flexible structures by applying the Chaboche model

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ABSTRACT

During seismic events, the gravity loads may cause a reduction of the lateral stiffness of structures; inelastic deformations combined with horizontal loads (P-Δ effect) can bring to a state of dynamic instability that obviously influences building safety. Especially for flexible structures, the P-Δ effect amplifies structural deformations and resultants stresses, and thus may represent a source of sideway collapse. Since this type of collapse is the result of progressive accumulation of plastic deformation on structural components, the specific objective of this works is to study this effect on a three floor metallic frame (made of aluminium alloy). A non-linear finite element (FE) model of the frame has been developed to study the dynamic non-linear behaviour of the structure, and compare it with the experimental results obtained from a scaled model of the real structure. The FE model, where a simple isotropic hardening behaviour was assumed for the material, was not able to reproduce the real behaviour of the structure. Rather, the correct description of the cyclic plastic behaviour of the material was essential for the numerical analysis of the structure. The characterization of the non-linear behaviour of the material was made by cyclic tension–compression tests on material specimen, from which the coefficients of Chaboche's model were properly calibrated. In this way, the finite element model of the structure provided results in optimum agreement with the experimental ones, and was able to predict the lateral collapse very well.

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1. Introduction

Throughout its service life, a civil structure can be subjected to seismic cyclic loading. These events may have a deep impact on building safety. Structural damage caused by earthquakes may in fact be due to excessive deformation of the elements, or may occur as a result of cumulative permanent deformations. The accumulated damage could affect the structural serviceability by even leading to a decreased structural safety. In the flexible ductile structures, vertical gravity loads combined with horizontal displacements (given by dynamic inputs as earthquakes) amplify structural deformations and stress resultants (P-Δ effect), and may be a source of sideways collapse. Indeed, in structural engineering, the P-Δ effect is usually defined as the impact of gravity loads when the structure is subjected to a lateral displacement which leads to a destabilizing, eventually critical, moment. A typical example is the so-called soft storey behaviour on the base floor, shown in Fig. 1. The global collapse may imply dynamic instability in a sideways manner, usually triggered by large storey drifts, which are amplified by plasticity accumulation on the system components [1].

In general, there are several simplified methods for a P-Δ analysis that is substantially a second-order analysis. The P-Δ effect can be determined by using second-order analysis and an iterative analysis is the common approach [2,3]. If a long rod is subjected to a large compressive force and is very close to buckling, the lateral stiffness of the rod has been reduced significantly and a small lateral load may cause the rod to buckle [4]. This general type of behaviour is caused by a change in the geometric stiffness of the structure. This stiffness is a function of the load on the structural member and can be either positive or negative [5]. The use of the geometric stiffness matrix (kg) is a general approach for including secondary effects in the static and dynamic analysis of all types of structural systems. However, in civil structural engineering it is commonly referred to as P-Δ analysis, which is based on a more physical approach. For example, in building analysis, the lateral displacement of a storey mass to a deformed position generates second-order overturning moments equal to the storey weights 'P' multiplied by the lateral displacements 'Δ'. Many techniques have been proposed for evaluating this second-order behaviour [4,6]. Rutenberg [7] summarized the publications on this topic and presents a simplified method to include these second-order effects. The P-Δ effect has to be implemented in the basic analytical formulation so that these effects can be consistently included in both static and dynamic analyses. The evolution of an initial local failure from element to element may cause progressive global collapse [8]. Global collapse may involve dynamic instability, which is usually triggered by large interstorey drifts, and is amplified by the P-Δ effect and by strength and stiffness deterioration of the structure [1].

Fig. 1 – Soft storey behaviour due to L' Aquila earthquake (2009).

If the yielding point is exceeded during cyclic loadings, two phenomena could cause damage: permanent deformation and ratcheting behaviour, which causes plastic strain accumulation [11]. In cyclic plastic deformation, local strain oscillates between minimum and maximum values without changing after the first few cycles. Instead, ratcheting plasticity produces a progressive increase in the plastic local strain at each cycle without any recovery. The plasticity accumulation is an aspect of fundamental importance, as being characterized by an increase in each cycle of deformation in one direction, that can lead to dynamic instability and then to collapse [12,13].

The formalization of a theory describing the mechanical behaviour of materials and structures due to cyclic loading capable of causing damage must concern two complementary aspects: the correct definition of appropriate collapse criteria, and the introduction of effective models of cyclic behaviour, capable of simulating non-linear local and global responses accurately [14].

Cyclic plastic deformation, which may occur on parts subjected to bending–unbending, cannot be accounted for by an isotropic model with sufficient precision, since it does not describe the Bauschinger effect that may occur in these cases [15]. Furthermore, the Bauschinger effect is responsible for the following relevant behaviours: an early yielding when strain is reversed, and a transient and permanent softening during plastic deformation, which may be associated with work hardening stagnation [16]. For all the reasons above, combined isotropic–kinematic constitutive models are necessary to capture the Bauschinger effect, and so to enhance the finite element simulation.

The first kinematic model was elaborated by Prager [17] and Ziegler [18]. They presented a linear kinematic hardening rule introducing the concept of the translation of the yield surface. This was accomplished through the so-called back stress tensor, which defines the current origin of the yield surface. Afterwards, thanks to the work of Armstrong [19] and Chaboche [20,21], a non linear model was defined expanding Ziegler's formulation. In this work, the Chaboche [20,21] model has been adopted as it is among the most reliable formulation in the literature and is implemented in many commercial FE software. The goal of this study is to understand the vulnerability of a flexible structure due to the mentioned lateral loads and P-Δ effect. Given the above considerations, this task can be accomplished by determining the cyclic behaviour in terms of plastic accumulation [9,10]. A case study, consisting of a full metallic scaled structure, is presented from