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Numerical study of a welded plate instability using the subloading surface model

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ABSTRACT

Instability in structural components has been widely studied to understand the elastic and inelastic behaviors of materials because of the risks associated with sudden failure of components under equilibrium conditions. However, most studies have been performed for various monotonic load configurations without considering the instability as a final step in a process induced by irreversible deformations that can arise even for small vibrations. This work investigates instability problems that may be caused by plastic strain during cyclic loading. This type of instability is difficult to study with conventional plasticity models because they fail in predicting irreversible deformation for changes in the stress state within the elastic domain. In contrast, unconventional theories abolish the distinction between plastic and elastic domains, allowing the material to exhibit a smooth elastoplastic response for every change in the stress state during a loading.

1. Introduction

A common feature of conventional plasticity models is the clear distinction between elastic and plastic domains (Drucker [1]). As a consequence, two different answers are possible depending on the position of the stress and on the direction of the stress increase in relation to the plastic potential. This assumption is a good approximation of real material behaviour and many engineering problems have been solved with this hypothesis. However, in some cases, the models give unrealistic predictions of material failure, especially when a large number of cycles are involved or where there are small stress vibrations around the yield surface.

Under cyclic loading conditions, elastic unloading is predicted as soon as the actual stress enters the elastic domain, and plastic deformation is not possible until the stress crosses the yield surface in the subsequent reload. This feature of the models presents a problem, because it leads to the formation of open hysteresis loops and consequently to an excessive accumulation of plastic deformation during the cycles is induced (Hashiguchi [2]).

In contrast, unconventional plasticity models abolish the separation between elastic and plastic domains, and allow the smooth generation of irreversible deformations whenever the stress satisfies the loading criteria (Fig. 1). This feature is important if we consider that although most structures are designed to operate within the conventional elastic domain for safety reasons, some loading conditions can cause a loss of equilibrium due to local phenomena.

Several unconventional models, referred also as cyclic plasticity models, have been proposed and they can be grouped into two categories. The first one is based on a kinematic hardening concept, creating a subyield surface within the conventional one, which keeps the same size and translates in the stress space with the development of irreversible contributions. The

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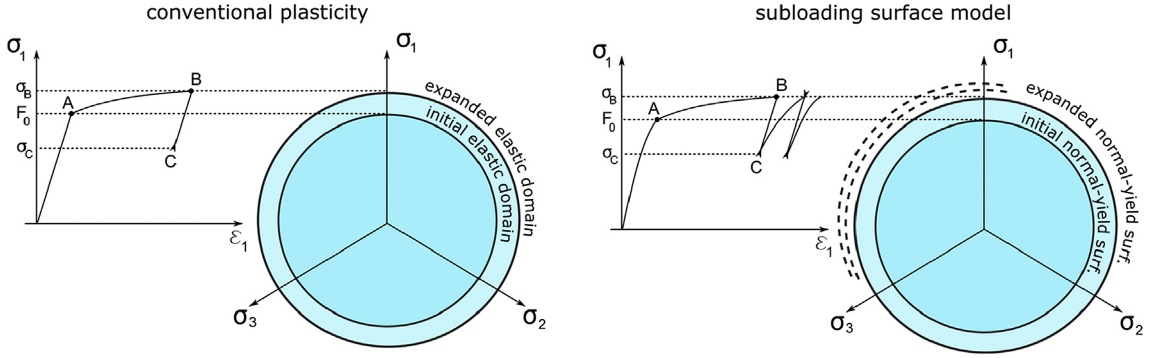

Fig. 1. Difference between conventional and unconventional plasticity models (isotropic hardening only).

second category is instead based on a concept of a subyield surface which expands and contracts in the stress space depending on the loading or unloading of the material.

Models such as the Multi Surface [3,4], the Two Surface [5], the Infinite surface [6] and the Single Surface [7] belong to the first category, whereas the Subloading Surface and the Extended Subloading Surface belong to the second. A detailed description of the kinematic hardening based theories and their features can be found in Refs. [2] and [8], where the defects characterizing this approach are also pointed out.

In detail, the Two Surface model introduced the simplification of the Multi Surface model, limiting to two the number of the surface adopted: the conventional yield surface and the subyield one, which encloses a pure elastic domain. In order to avoid singularities, the subyield surface cannot intersect with the plastic potential, therefore, a proper translation rule has to be given as in Hashiguchi [9,10]. This approach has been widely adopted and was further developed by several authors (Ohno [11]; McDowell [12,13]; Yoshida and Uemori [14,15], Skallerud [16]), especially for metals. However, some issues such as the violation of the continuity and smoothness conditions, a sudden decrease of the plastic modulus when it reaches the yield surface and an excessively large accumulation of plastic strain in unidirectional cyclic loadings (i.e. stress ratio $R = 0$), could not be completely overcome.

The local ductility is a relevant aspect for the evaluation of the stability of steel structures that undergo small vibrations, seismic loads or other cyclic loads of different nature. The accumulation of irreversible contributions and the increments of out-of-plane displacements lead to a more complex buckling behaviour of the one induced by a monotonic loading [17,18]. In particular, steel plates are widely used as primary components for many structural systems such as: aircraft, ships and offshore structures, and they have a fundamental contribution to the structure stability. The instability phenomena of these components are well known and they have been studied intensively in the last few decades, however, the role of the residual stress and plastic strain fields deriving from a welding process or the formation of plastic hinges for small vibrations in the neighbourhood of the yield stress have not been completely understood yet [19–22].

The present paper aims to enrich the panorama on this topic, presenting low-cycle fatigue analyses with a maximum load lower than the monotonic critical one for a welded plate, highlighting the role of the residual stress and plastic fields on the number of cycles to instability. The investigations were carried out by means of the extended subloading surface model [23] using an implicit integration scheme based on the cutting-plane algorithm. The motivations of this choice can be justified with the ability of the model to catch a realistic plastic strain accumulation through cycles under different boundary conditions, thanks to the insertion of a mobile similarity center, not present in the initial formulation [24]. The subloading surface model is in fact able to describe the accumulation of irreversible contribution that arises as a consequences of cyclic loading in the neighbourhood of the yield surface and that may cause the loss of equilibrium in thin compressed structures. Conventional plasticity models are not able to describe such behaviour since the material response for a loading condition within the so-called elastic domain will always generate reversible strain (see Fig. 1). The implicit integration scheme was firstly presented in Hashiguchi [2] and Hashiguchi et al. [25], with a subsequent finite elements application in Hashiguchi et al. [26]. The main aspects of the present work are listed as follows:

- The results from a coupled thermomechanical welding simulation for a plate are presented and discussed;
- A mechanical cyclic loading condition is applied on the welded plate considering two constraining conditions and investigating the buckling phenomenon related to the development of plastic deformations;
- The effects of the residual stress and cumulative plastic strain fields on the number of cycles necessary for structure failure are analysed.

2. The extended subloading surface model

Before describing the numerical analyses, the constitutive equations of the extended subloading surface model will be briefly introduced. A more detailed discussion of these equations is presented in Refs. [2] and [25]. Classical theories