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Design of low strength-high hardening metal multi-stiffened shear plates

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ABSTRACT

In this paper design curves for low strength-high hardening metal multi-stiffened shear plates are provided, based on both experimental tests and parametric numerical analyses. To this aim, an almost pure aluminum is considered as base material, it being characterized by a yielding stress point of about 20 MPa and a hardening ratio higher than 4.

An "initial stability" curve, which is useful to determine service limit conditions for metal plates in shear, is outlined with the aim of establishing the early buckling phenomena. Then, design curves providing the reduction factor of the ultimate strength of the plate in shear duly accounting for buckling phenomena are proposed as a design tool for system dimensioning.

Finally, the issue related to the design of stiffeners, which are applied to delay shear buckling and to improve the plate hysteretic performance, is investigated.

The current study represents an extension of the outcomes provided in a previous paper [4] (Brando and De Matteis, 2011), where the above design curves have been provided for hardening aluminum shear plates without stiffeners.

1. Introduction

In the last two decades, thin low strength shear panels have been proposed as hysteretic dampers for seismic protection of steel frames [8] and reinforced concrete structures [22,11,18]. The main prerogative is the activation of the dissipative function for reduced deformations, allowing an advantageous application of the capacity design concept for protecting the primary structural elements, i.e. beams, columns and connections. In addition, they are characterized by a far post elastic stiffness, high isotropic hardening, as well as large ductility. Finally they could offer stable and large hysteretic cycles even under severe external demands, either yielding in shear or by developing tension field mechanisms.

First significant researches on low yield strength steel shear panels were carried out by Nakashima et al. [23,24]. Experimental tests and numerical analyses were performed in order to evaluate the cyclic behavior of specimens characterized by different width-to-thickness ratio. These panels were made of low-yield steel, characterized by low carbon contents, having a nominal elastic strength of 120 MPa and an available ductility of almost 50%. Provided the difficulty of retrieving this type of material in the worldwide markets, low strength aluminum has been proposed as an alternative for manufacturing dissipative devices. An example is provided in Rai and Wallace [26] and Jain et al. [21], where two different aluminum materials, namely the AW 3003-O and the AW 6061-O (in a fully soft and annealed condition – temper O) alloys, have been adopted, as base material. The results obtained by experimental tests showed that such devices could offer a good performance when subjected to repeated cyclic loadings.

In Europe, the heat threaded EN-AW 1050A alloy, which is an almost pure aluminum further improved by a proper annealing able to produce a profitable softening with the annulment of existing microscopic and macroscopic residual stresses [9] (De Matteis et al., 2007), has been proposed. It is characterized by a conventional yield stress (0.2% proof strength) of about 20 MPa, a ductility of 30–40% and a hardening ratio of about 4. Several experimental and numerical studies highlighted the effectiveness of pure aluminum shear panels for the seismic protection of buildings, also for high structural demands. Today it is possible to assert that this panel typology is very competitive with respect to the other most popular metallic dampers, such as BRBs ("Buckling Restrained Braces", [3]), ADAS ("Added Damping and Stiffness", [2]) devices, and friction dampers [5]. For this reason, this paper aims at providing proper tools to be used for design. On the one hand, the spacing of the stiffeners necessary to mitigate or completely avoid the detrimental effects caused by shear buckling has to be considered. For this reason, a curve providing the reduction factors of the ultimate strength, as a function of the slenderness determined by such a

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spacing, is given. Moreover, as the control of the triggering of the initial stability represents an important issue for determining serviceability limit state conditions, an "initial stability curve", that gives the shear forces that activate the tension field mechanisms, is also supplied.

On the other hand, design formulations for providing the flexural stiffness to be assigned to the stiffeners in such a way they are not involved in the buckling modes of the plate due to coupled instabilities have to be outlined.

The above issues are somehow dealt with by EUROCODE 9 [17] with reference to web panels of girders made of common aluminum alloys which, indeed, are commonly conceived in order to work in the elastic field. Nevertheless, in the specific case under investigation, further studies are necessary in order to take into account the peculiarity of the adopted material, which is characterized by very low yield strength and high hardening, as well as for taking into account buckling in plastic range, which could limit the dissipative function of these special devices.

To this purpose, based on FEM numerical models previously calibrated on available experimental tests carried out by the authors [12,13], design curves for dimensioning multi-stiffened pure aluminum shear panels, together with provisions on the effectiveness of flexural stiffeners, are provided in current paper.

2. The numerical model

2.1. General

Three main experimental tests, carried out by the authors on multi-stiffened plate in shear with different stiffeners' spacing, have been used to calibrate a FEM model, which has been set up by the ABAQUS nonlinear software [1]. In Fig. 1, the numerical models with the adopted mesh, which has been imposed on the basis of a sensitivity analysis, are shown. In the same figure, the geometry and nomenclature of specimens are given. Additional details are provided in De Matteis et al. [13], whereas both the implemented modeling approach and analysis procedures are fully described in Brando and De Matteis [4].

The plates have been subjected to quasi-static diagonal cyclic forces selected according to the loading protocol given by ECCS-CECM [15]. Initial imperfections, mainly due to the stiffeners welding, have been taken in account considering as initial deformed configuration a combination between the buckling mode shapes got from the first and third eigenvectors of a previously implemented buckling analysis and assigning to both of them a maximum out-of-plane displacement equal to 1/100 of the free length involved in buckling phenomena, which has been selected according to a sensitivity analysis. Such two modes have been combined to each other since they mainly involve different panel portions detected by the transversal ribs.

As far as the material is concerned, engineeristic mechanical features of the considered aluminum alloy, which represents an innovative material for structural applications, are provided in De Matteis et al. [14], where detailed information on both the monotonic and cyclic behavior is given. For numerical analysis, a model of true strain–true stress relationship based on experimental tests has been considered [10]. For a better comprehension of the outcomes of the current paper, it is important to underline that the material under consideration is characterized by a very large hardening ratio, namely $f_u/f_{0.2} = 4.65$ in terms of true stress, which is much higher than common aluminum alloys referred in Eurocode 9.

2.2. Calibration of the proposed model

The numerical analysis of the reference tests and the consequent detailed comparison with experimental results, allowed to check the reliability of the proposed model. In Fig. 2, such a comparison is provided in terms of hysteretic cycles, up to diagonal displacement demands ranging from −40 mm to +40 mm.

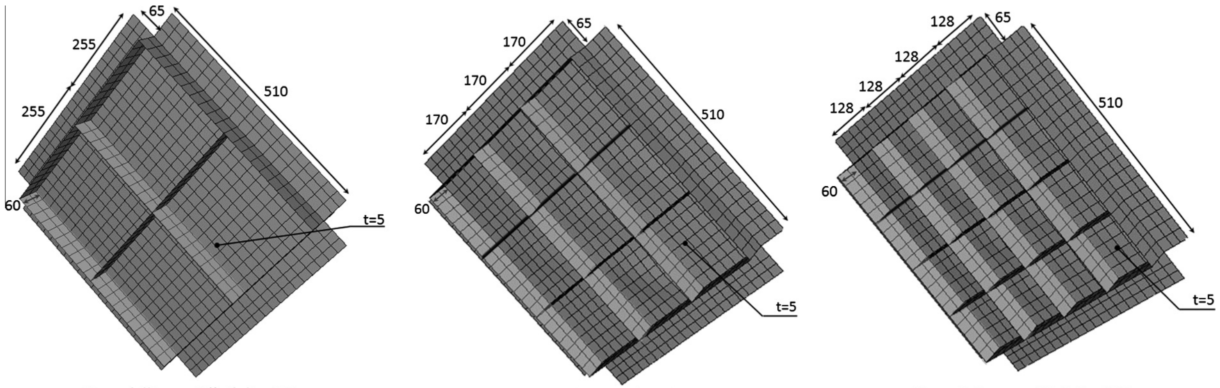
These limits correspond to a shear strain of almost ±10%, after which experimental tests revealed the failure of the perimeter connecting system and the fracture of the base plate due to low cyclic fatigue. Therefore such a ductility level can by assumed as a limit reference value for the shear panel typology under investigation.

The obtained results evidence the capability of the numerical model to interpret correctly the behavior of tested shear panels in terms of strength, stiffness and energy dissipating features, including the pinching effects on the hysteretic cycles due to the buckling phenomena, which is evident for panel type 2.

2.3. Numerical vs. experimental evidences

The reliability of the proposed models has been also checked by comparing the numerical and the experimental deformed shapes of the plates during the loading process. As stated in De Matteis et al. [13], the experimental tests evidenced three main behavioral phases, which are activated for different shear strain demands depending on the number of applied stiffeners: (i) plate working in pure shear, (ii) plate working according to a tension field mechanism, (iii) collapse of the plate by developing of fractures in the center of the subpanels and/or in the perimeter connecting system.

As far as the first behavioral phase is of concern, the analysis of the experimental evidences revealed that the first buckling phenomena arose for a diagonal displacement equal to about ±5.00 mm, ±10.00 mm and ±20.00 mm for panel "type 2", "type



Panel "type 2" (b/t=50) *Panel "type 3" (b/t=33)* *Panel "type 4" (b/t=25)*

Fig. 1. Analysed shear plates and proposed FEM numerical models.