Journal of Constructional Steel Research 123 (2016) 41–52

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental tests and optimization rules for steel perforated shear panels

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form 8 April 2016
Accepted 23 April 2016
Available online 6 May 2016

Keywords:
Steel shear walls
Perforated shear plates
Dampers
Seismic protection
Pinching
Experimental tests
Design rules
Numerical analysis

ABSTRACT

The paper presents the main results obtained downstream experimental and numerical study on steel perforated shear panels. Primarily, the response of the studied devices determined by cyclic tests is analysed. It is evidenced that the hysteretic performance of steel perforated shear panels might be detrimentally influenced by pinching effects and softening due to cumulated damage produced by lateral-torsion buckling that may arises when the plate portions delimited by contiguous perforations are excessively slender. Based on tests results, a suitable analytical formulation for the prediction of the strength at several shear demands, accounting for the influence of the above detrimental effects, is provided. Also, a parametric study based on a FEM numerical model calibrated on the basis of the experimental tests is developed. Two main goals are achieved: *i*) to establish the influence of the main geometric parameters on the panel hysteretic response, with particular regard to the pinching effects provoked by buckling phenomena; *ii*) to determine analytical formulations able to give back the ratio between the "pinching" strength and the maximum strength, the former being the force corresponding to a null shear strain in a cycle. Therefore a useful predictive tool for defining the optimal perforation geometry to be adopted as a function of the expected shear demand is provided.

1. Introduction

Nowadays, the application of weak metallic shear panels into new and existing structures is considered to be a viable and effective way for protecting the primary structural members from damage, even under severe seismic shacking. In fact, these systems are able to guarantee a large dissipative capacity, activated for limited structural demands, due to the high ductility of the employed base material and the effectiveness of the developing resisting mechanisms.

The main prerogative that must be assured for these dampers is that their response must not be influenced by the detrimental effects generated by buckling phenomena. Such phenomena can arise when the base plate is characterized by high slenderness (either global or local) that can produce pinched hysteretic cycles and fatigue due to cumulated damage.

Several types of weak metallic shear panels have been proposed in the last two decades, also for retrofitting existing r.c. buildings [1–2]. Most of them have been realized by using low yield stress point materials [3]. Nakashima proposed to use a steel type with 0.2% offset yield stress is 120 MPa [4]. De Matteis et al. [5–6] used an almost pure aluminium characterized by a conventional yielding strength of about 25 MPa and a ductility of about 40% [7]. Similarly, miscellaneous aluminium alloys were profitably used by Rai et al. [8–9]. All the aforementioned studies concerned relatively thin plates on which transversal stiffeners were applied in order to shift the activation of potential buckling phenomena in the inelastic field.

As a convenient alternative, the authors of this paper [10–11], and later on also Deng et al. [12], proposed to use very thin plates, made of either innovative or traditional materials, where buckling phenomena are inhibited by special elements restraining the out-of-plane displacements, but that do not interact with the base plate when it undertakes membrane strains. Such a system applies the basic concept of buckling restrained braces (BRBs) in the bi-dimensional space, offering the same advantages from the dissipative point of view [13], but allowing a more convenient control at collapse because of the post-critical resources of the plate in shear.

More recently, it has been recognized that another fruitful way for obtaining dissipative shear panels consists in weakening the base plate by removing some parts. On the one hand, this solution reduces the shear strength, allowing accomplish more easily the capacity design criteria; on the other hand, it allows to mitigate the negative effects generated by buckling phenomena by the opportune variation of the internal stress pattern.

This paper presents the results of an experimental and numerical study carried out on steel perforated shear plates. In particular, the outcomes of two full scale tests are shown, highlighting the most

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http://dx.doi.org/10.1016/j.jcsr.2016.04.025
0143-974X/

influencing experimental evidences, with particular regard to those phenomena that could reduce the dissipative capacity of the studied devices. Then, the obtained experimental results are used in order to set-up a sophisticated FEM model that is subjected to an extensive parametric analysis that allows to provide design rules to be used for the optimization of the holes configuration.

Mainly, the present research aims at achieving the following goals:

- to investigate the hysteretic behaviour of very thin perforated shear panels by experimental tests;
- to put into evidence potential detrimental mechanisms under cycles of different amplitude;
- to optimize the panel response, by means of numerical analyses carried out on calibrated FEM models, in terms of perforation geometrical features, also accounting for the thickness of the base plate;
- to propose design formulations that give back the panel configuration according to the expected performance.

2. State-of the art

2.1. Experimental studies

The results of experimental tests are very useful to analyse the response of weakened shear panels. In fact, the variation of the internal stresses pattern due to the removed portions of plate could lead to an unexpected behaviour.

Some interesting experimental analyses on weakened shear panels are present in literature. Hitaka and Matsui [14] tested forty-two shear plates with several vertical slits. The shear force acting on the system is commuted in a bending mechanism for the plate portions confined by two slits, which undergo large flexural deformations producing a significant dissipative capacity. Recently, this type of system has been considered by Pohlenz [15], who studied the influence of slits layout and gave analytical formulations in order to assess the initial stiffness, the maximum strength, the force levels triggering buckling and the dissipated energy.

Vian, Bruneau and Purba [16] carried out experimental tests on shear panels weakened by holes arranged in a staggered configuration. They provided design formulations of the shear strength accounting for the holes diameters and spacing, also considering the influence of the surrounding frame stiffness.

Valizadeh et al. [17] investigated the cyclic response of six 1:6 scaled specimens of perforated shear walls made of plates with a central circular opening. They quantified the influence of the hole diameter on the loss of dissipated energy due to the pinching effects on the hysteretic cycles. Furthermore, they highlighted the presence of brittle failures around the perforations when very thin plates are adopted.

Alavi and Nateghi [18], by means of experimental tests on 1:2 scaled single-storey SPSWs, proved that perforated diagonally stiffened shear panels could allow the same stiffness of un-ribbed solid panels, with an increase of ductility of more than 14%. In addition, an extension of the design formulation of the shear strength given previously by other Authors was provided, accounting for the diagonal stiffeners contribution.

Chan et al. [19] introduced a Perforated Yielding Shear Panel Device (PYSPD), considering three perforation layouts and proving that, for certain plate slenderness, the obtained hysteretic cycles are stable and a high ductility is achievable, with a potential large dissipation capacity that can be exploited under seismic force, in particular for rectangular patterns of perforations.

2.2. Numerical analyses

The study of metal perforated shear plates has been profitably developed also by using FEM numerical models. On the one hand, numerical analysis allows identifying the internal stress patterns that arise owing to the perforation layout. On the other hand, it consents to vary easily the geometrical and mechanical properties to carry out extensive parametric analyses for selecting optimal configurations of holes.

Purba and Bruneau [20] analysed an entire steel perforated shear wall where the base plate worked according to a weakened strip model originated from perforations arranged in a staggered configuration. In a first step the Authors performed finite element analyses on local models of single strips weakened by holes with diameters ranging from 10 mm to 300 mm. Then, they considered the model of the whole perforated shear wall in order to investigate the relationship between the perforation diameter and the infill panel strain, in order to verify the accuracy of the individual strip model results and to analyse the influence of the perimeter frame stiffness on the stress/strain of the plate.

Bhowmick [21] carried out nonlinear pushover analyses on series of single storey perforated steel plate shear walls with different aspect ratios and perforation diameters, confirming the reliability of an analytical equation for predicting design shear strength. Moreover, the forces in the surrounding frame members of multi-storey buildings, deriving from the above shear strength, were analysed.

Pellegrino et al. [22] studied the influence of one perforation on both buckling strength and post-critical behaviour of steel plate in shear, accounting for several holes dimensions, shape and positions, as well as considering different plate slenderness and aspect ratios.

In [23], on the basis of the experimental tests carried out by Egorova et al. [24], a numerical model on a steel plate with a pattern of holes leaving ring-shaped portions of steel connected by diagonal links was developed. The dissipative capacity of the system was guaranteed by the plastic mechanism activated when steel circular rings deformed into ellipses; moreover the presence of the diagonal links allowed the mitigation of possible out-of-plane buckling.

3. The experimental campaign

3.1. Tested shear panels

The two tested Perforated Shear Panels, that henceforth will be referred as PSP1 and PSP2, were made of 2.5 mm thick plates. The geometric features are described in Fig. 1, where the sizes are expressed in mm. Each specimen was obtained by applying nine perforations according to a rectangular pattern. As reported in [19], this type of choice ensures a better performance with respect to a staggered configuration. Hole diameters of 127.5 mm and 107.4 mm were imposed for PSP1 and PSP2, respectively.

Each plate was connected to a perimeter articulated frame made of four built up members obtained by coupling two UPN 120 channel section profiles. The plate-to-perimeter frame connections were realized by 8.8 grade M14 steel friction bolts spaced by a pitch of 50 mm.

In addition, in order to increase the contact area between the plate and the built up members, double sided internal 10 mm thick plates (two for each edge of the articulated frame) were applied, as it can be seen in Fig. 2a where the panel is shown during the assemblage process.

The experimental set-up was completed by two hinged steel jigs connecting two opposite vertices of the panel to the MTS machine used for carrying out pseudo-static cyclic tests (see Fig. 2b).

The material mechanical features of the plates were preliminarily investigated by means of uniaxial tensile tests. They were carried out on dog-bone specimens extracted from the same metal sheeting from which both the two plates were obtained. In particular, four coupons (namely H1, H2, H3 and H4) about the lamination direction and five coupons (namely V1, V2, V3, V4 and V5) about the perpendicular one were taken out.

The obtained results, which are reported in Fig. 3 together with the curves fitting the average values and the true strain-true stress, showed that the yield stress measured in the lamination direction (about