ON THE USE OF PERFORATED METAL SHEAR PANELS FOR SEISMIC-RESISTANT APPLICATIONS

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ON THE USE OF PERFORATED METAL SHEAR PANELS FOR SEISMIC-RESISTANT APPLICATIONS

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Abstract. *Steel Plate Shear Walls (SPSWs) are an innovative system able to confer to either new or existing structures a significant capacity to resist earthquake and wind loads. Many tests have shown that these devices may exhibit high strength, initial stiffness and ductility, as well as an excellent ability to dissipate energy. When traditional SPSWs are used as bracing devices in buildings, they may induce excessive stresses in the surrounding structure, so to require the adoption of large cross-section profiles. For this reason, perforated steel panels, which are weakened by holes aiming at limiting the actions transmitted to the surrounding frame members, represent a valid alternative to the traditional panels. In this work, a FEM model of perforated panels has been calibrated on the basis of recent experimental tests. Subsequently, a parametric FEM analysis by changing the number and diameter of the holes, the plate thickness and the metal material, has been carried-out. Finally, an analytical tool to estimate the non-linear response of perforated metal shear panels has been proposed.*

1 INTRODUCTION

The seismic protection system based on the use of Steel Plate Shear Walls (SPSWs) consists of stiff horizontal and vertical boundary frame elements and infill plates. Generally, SPSWs are located in perimeter frames of the main structure or around stair cases, they occupying an entire span or a part thereof and they can be stiffened or unstiffened, depending on the design philosophy. When unstiffened thin plates are loaded in their plan, they immediately buckle, but additional loads can be carried due to the tension-field mechanism, i.e. the development of tensile strips in the plate diagonal direction [1]. As a consequence, the boundary frame members have to be designed to support the tension-field mechanism developed in the plate. This action may induce in the frame members large force demands, which give rise to the adoption of high depth profiles. A number of solutions have been proposed to alleviate this condition, based on connection of the infill plate to the beams only [2], on vertical slits [3], on thin light-gauge cold-rolled steel [4], on low-yield strength steel [5,6], on perforated SPSW [6] and on aluminium plates [7,8].

In this paper the attention is focused on the use of perforated SPSWs, in order to limit the construction cost deriving from the installation of such devices into the structure.

2 PREVIOUS RESEARCHES ON UNSTIFFENED PERFORATED PANELS

The first studies aimed at evaluating the behaviour of unstiffened steel panels were presented during the first ‘80s of last century [9]. In 1991, on the basis of experimental diagonal tests performed on SPSWs within a pinned joint frame, Roberts and Sabouri-Ghomi [10,11] proposed a theoretical method, namely the Plate-Frame Interaction (PFI) method, for calculating the shear capacity and the stiffness of the steel device.

In 2005, Sabouri-Ghomi et al. [12] presented a correction of the PFI method by introducing two modification factors, C_{m1} and C_{m2}, taking into account beam-to-column connections, plate-to-frame connections and the effect of both flexural behaviour and stiffness of boundary elements. By applying the above modification factors, the contribution of the panel only can be obtained as follows, in terms of shear capacity F_{wu} and stiffness K_w:

$$F_{wu} = b\ t\ \left(\tau_{cr} + \frac{C_{m1}}{2}\ \sigma_{ty}\ sin2\vartheta\right) \tag{1}$$

$$K_w = b\ t\ (\tau_{cr} + \frac{C_{m1}}{2}\ \sigma_{ty}\ sin2\vartheta)/[d\left(\frac{\tau_{cr}}{G} + \frac{2\ C_{m2}\ \sigma_{ty}}{E\ sin2\vartheta}\right)] \tag{2}$$

where t, b, d are the thickness, width and height of the steel plate, respectively, E and G are the normal and shear elasticity modulus of the plate's materials, σ_{ty} is the tension field stress in the plate yielding condition, ϑ is the diagonal tension-field angle, measured from the horizontal direction, and τ_{cr} is the critical buckling shear stress, evaluated according to the Timoshenko's theory. The modification factors were limited as follows: $0.8 < C_{m1} < 1.0$ and $1.0 < C_{m2} < 1.7$. The authors recognized that these values will need further refinement as more test results will become available in the future.

Purba and Bruneau [6], experimentally tested a shear panel with a configuration of 20 regularly spaced circular holes. Through a calibration FEM study, they proposed the factor $(1 - 0.7D/S_d)$, where D is the hole diameter and S_d is the diagonal distance between each perforation line, to reduce the shear strength of the perforated SPSWs with a regular perforation pattern.

A series of unstiffened SPSWs with different perforation patterns were studied by Bhowmick [13]. On the basis of analytical considerations, the author proposed the reduction factor $[1 - \beta\ N_r D/(b\ cos\alpha)]$, where α is the tension-field angle, D is the circular hole diameter, b is the perforated infill plate width, N_r is the maximum number of diagonal strips and β is a regression constant obtained from the FEM analysis, to fit the system behaviour.

In 2012, eight centrally perforated panels, with two plate thicknesses and four D/b ratios, were tested under cyclic loading by Valizadeh et al. [14]. The obtained results showed a stable behaviour of the panels for large displacements up to a drift of 6%. It can be observed that, during the loading phase, the stable cyclic behaviour of specimens in the non-linear range caused mostly a dissipation of energy, but the presence of an opening at the panel centre provoked a noticeable decrease in the energy absorption of the system.

3 DESCRIPTION OF THE PROPOSED FEM MODEL

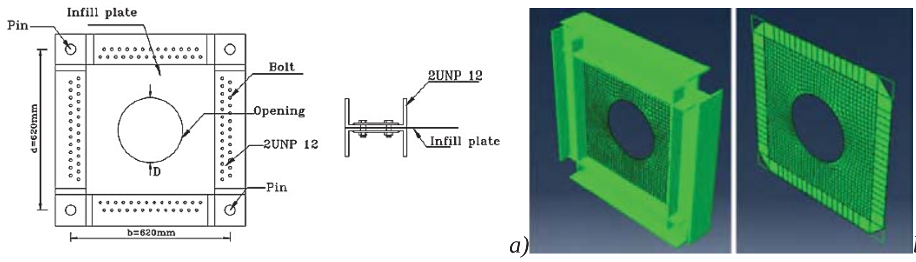
A FEM model implemented in ABAQUS [15] is proposed for simulating the behaviour of shear panels under cyclic and monotonic loading. In order to focus attention on the behaviour of the plate only, the proposed FEM model has been built on the basis of the experimental test setup recently arranged by Valizadeh et al. [14] on panels within pinned joint frames made of UPN120 coupled profiles (see Figure 1a).

Both plate and frame are modelled with 3D deformable elements. Plate is modelled by S4R shell elements, while frame is modelled with B31 beam elements. The beam-to-column connections are modelled by HINGE connectors. By preliminarily sensitivity analysis, an approximate mesh size of 15 mm has been chosen for the plate. The points of the lower hinges are restrained to the translations in order to simulate a rigid base. The points of the upper beam are restrained towards out-of-plane displacements in order to simulate the presence of lateral supports in that direction. The plate-to-frame connections are modelled by AXIAL connectors. For simplicity, an equivalent centroid row of connectors for each side is adopted. The contact of two UPN120 on the plate is simulated by restraining the out-of-plane displacement of the plate in an extended area of 60 mm from the edge. The mesh is diversified in this plate area to reflect the real location of the coupled bolts.

The model takes into account the mechanical and geometrical non-linearity of the system. The plate is modelled by an elastic-plastic-hardening material. In particular, an isotropic hardening is used for the monotonic analysis, while a combined hardening is used for cyclic analysis. The frame is modelled by an elastic material. In order to take into account the initial imperfections, deformed shapes related to the plate instability modes are assigned to the SPSW. Moreover, some imperfections due to bolted connections localized along the panel perimeter (hole spacing, bolt-hole clearance, tightening pressure) can be introduced in the FEM model. It is possible take into account these imperfections through AXIAL connectors, whose behaviour is opportunely calibrated on the basis of experimental evidences [14]. A representation of the proposed FEM model is shown in Figure 1b.

4 THE FEM MODEL CALIBRATION

The FEM model previously described has been calibrated by comparing the predicted behaviour to the test results of Valizadeh et al. [14]. In these tests, eight panels filling a hinged joint frame have been considered. The centreline-to-centreline spacing between the two coupled UPN120 beams and columns of the frame has been set equal to 620 mm (see Figure 1a). However, the geometrical dimensions of internal plates have been assumed equal to 500x500 mm, by considering the depth of the applied channel sections of the framing system. The properties of experimental specimens are listed in Table 1, where σ_{ym} and σ_{um} are the mean yielding and ultimate stress of panels, respectively. Experimental specimens have been tested under a cyclic loading process with five cycles up to a drift of 6%.



a) *b)*

Figure 1. Geometrical representation (a) and proposed FEM model (b) of the specimens tested by Valizadeh et al. [14].

Table 1. Properties of the specimens tested by Valizadeh et al. [14].

Specimen	Thickness (mm)	Opening (mm)	σ_{ym} (MPa)	σ_{um} (MPa)	Failure mode
SPW1	0.70	0	180	300	plate-frame connection
SPW2	0.70	100	180	300	no failure
SPW3	0.70	175	180	300	no failure
SPW4	0.70	250	180	300	no failure
SPW5	0.37	0	299	375	plate-frame connection
SPW6	0.37	100	299	375	fractures around hole
SPW7	0.37	175	299	375	fractures around hole
SPW8	0.37	250	299	375	no failure

For the sake of brevity, just some of the obtained results are reported in the following. An initial out-of-plane imperfection proportional to the first instability mode with amplitude of 1 mm has been assigned for all panels. The panel numerical behaviour has been experimentally calibrated on the basis of the axial stiffness of the connectors. For example, the SPW3 panel has been calibrated by adopting an axial stiffness of the connectors K_c equal to 1200 N/mm. This panel has shown, both experimentally and numerically, to attain a maximum drift of 6% without failure. The experimental-to-numerical comparison in terms of both hysteretic curve and panel deformed shape is shown in Figure 2.

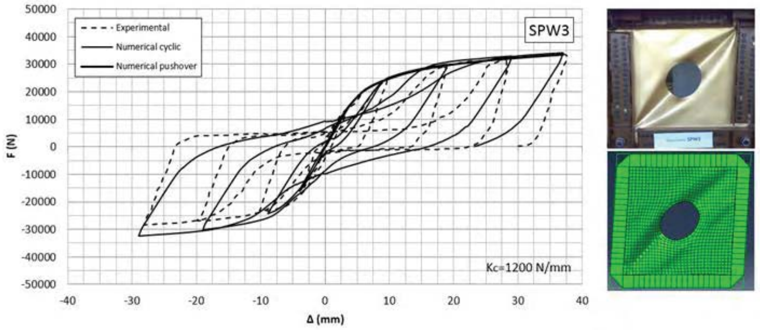


Figure 2. Numerical calibration of experimental results on the SPW3 specimen tested by Valizadeh et al. [14].

The final results of the calibration phase showed that the FEM model is able to acceptably simulate the behaviour of shear panels in terms of both initial stiffness and shear strength. A less accuracy has been also observed in simulating the pinching effect, due to local instability occurrence. However, the FEM model can be considered as sufficiently reliable, since it accurately estimates the total amount of energy dissipated by the examined system.

5 PARAMETRIC ANALYSIS ON PERFORATED PANELS

In the present study, 13 different configurations of perforated shear panels have been analysed. These configurations differ each other in terms of disposition, number and diameter of holes (see Figure 3), material (steel or aluminium) and plate thickness. Following the dimensions of specimens tested in [14], steel plates with a thickness of 0.37, 0.70 and 1.40 mm have been considered. In addition, aluminium plates with thickness of 3.70 and 7.00 mm have been also used in order to cover the same resistance range of the steel panels.

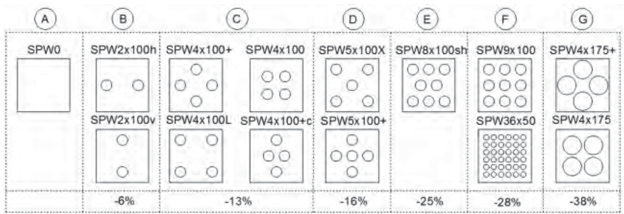


Figure 3. Groups of analysed panels and identification of drilling percentages. The prefix SPW is followed by: the number of holes, the hole diameter (mm) and a symbol identifying the hole pattern (v: vertical, h: horizontal, L: large, +: vertical cross, c: close, X: diagonal cross, s: staggered).

The mechanical characteristics of the used materials are shown in Table 2. As the calibration of the model has been done on the basis of some existing tests [14], the same steel quality has been adopted. The mechanical properties of aluminium correspond to "ad hoc" material obtained by a thermal treatment, as suggested in [16], which lowers the elastic limit and amplifies the ultimate elongation. The plate-to-frame connection is analogous to the one used in [14], with a mean value of the connector axial stiffness equal to 1200 N/mm. Any possible crisis of the plate-to-frame connection has been considered. The initial imperfection of plates has been given with an out-of-plane deformation having amplitude of 1 mm, similar to the panel first instability mode. In the same way of the experimental tests, the FEM analyses have been pushed until either the formation of fractures around holes or the attainment of the maximum allowable displacement (drift of 6%). Tables 3 and 4 provide a summary of the contribution offered by perforated panels in terms of strength and initial stiffness, respectively. A large variety of shear strength contribution of perforated panels, larger than those offered by traditional panels, can be identified in

Table 3. This can be an advantage because the choice of an appropriate drilling configuration of panels can lead to the desired requirement in improving the structure strength, where panels are inserted.

Table 2. Mechanical properties of used materials in the parametric analysis.

Material	E (MPa)	ν	σ_y (MPa)	σ_u (MPa)	ε_u
Steel	200000	0.3	180	300	0.15
Aluminium (AW 1050A)	70000	0.3	18	70	0.35

Table 3. Comparison between analysed panels in terms of shear capacity.

Specimen	Shear capacity (KN)				
	steel			aluminium	
	t=0.37mm	t=0.70mm	t=1.40mm	t=3.70mm	t=7.00mm
SPW0	21.94	41.10	76.39	27.12	51.22
SPW2x100h	19.54	37.18	69.00	24.75	47.94
SPW2x100v	18.64	34.50	68.03	24.74	47.91
SPW4x100+	17.70	32.70	62.96	23.03	44.73
SPW4x100+c	16.30	30.32	56.92	22.25	43.63
SPW4x100L	16.18	30.62	58.88	21.99	43.71
SPW5x100X	15.62	29.14	58.06	21.28	41.96
SPW4x100	15.46	28.72	56.58	21.41	41.18
SPW5x100+	15.14	28.97	54.83	20.69	40.82
SPW4x175+	12.52	22.12	42.22	16.95	34.22
SPW8x100sh	11.31	20.81	40.97	17.15	35.48
SPW9x100	11.06	19.61	37.11	15.32	32.12
SPW36x50	10.14	18.82	35.90	17.59	35.15
SPW4x175	9.54	16.54	30.54	12.19	27.10

Table 4. Comparison between analysed panels in terms of initial stiffness.

Specimen	Initial stiffness (KN/m)				
	steel			aluminium	
	t=0.37mm	t=0.70mm	t=1.40mm	t=3.70mm	t=7.00mm
SPW0	4061	5132	5698	5685	5685
SPW2x100h	4071	5031	5608	5614	5648
SPW2x100v	4042	5003	5583	5590	5641
SPW4x100+	4030	4873	5523	5550	5633
SPW4x100+c	3930	4818	5528	5534	5611
SPW4x100L	3652	4746	5564	5567	5595
SPW5x100X	3580	4660	5530	5541	5618
SPW4x100	3452	4625	5504	5507	5686
SPW5x100+	3353	4608	5466	5441	5576
SPW4x175+	3623	4515	5167	4918	5409
SPW8x100sh	3403	4284	5377	5329	5542
SPW9x100	2772	4263	5247	5168	5670
SPW36x50	3126	4134	5097	4965	5350
SPW4x175	1795	3991	4463	5159	5298

The comparisons in terms of hysteretic curves for panel SPW5x100+, having a percentage of holes ($\rho_{holes} = A_{holes}/A_s$) equal to 16%, are reported in Figure 4. From this figure, it is possible to note that the aluminium panels have better dissipative function than steel ones. For the former panels, the hysteretic cycles appear to be larger and characterized by a negligible pinching effect. In addition, thicker panels are susceptible to undergo high drifts without the formation of failures around holes. The final deformation shape of the analysed panels is shown in Figure 5.

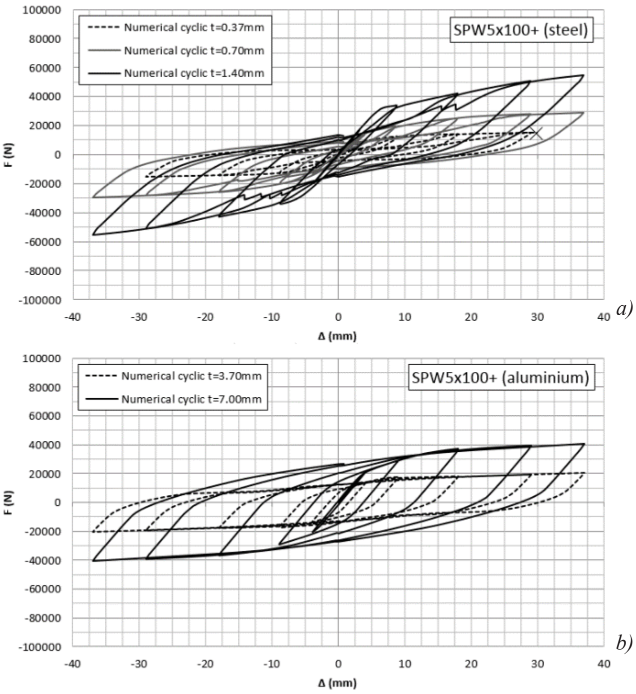


Figure 4. Hysteretic curves of SPW5x100+ steel (a) and aluminium (b) panels with different thicknesses.

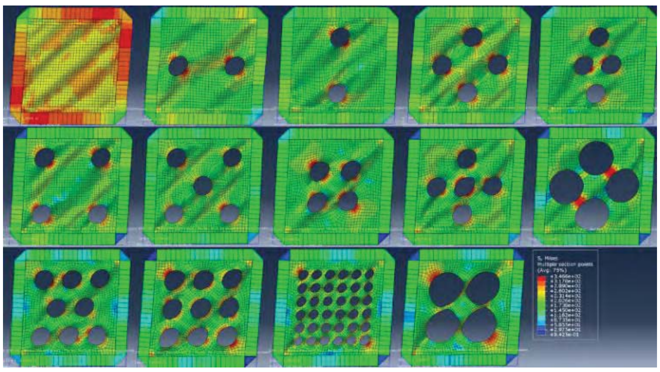


Figure 5. Final deformation of analysed panels and distribution of internal stresses.

On the basis of the obtained numerical results, the design charts reported in Figure 6 are derived. These diagrams can be used to evaluate the modification factors C_{m1} and C_{m2}, which appear in Equations (1) and (2) proposed by Sabouri-Ghomi [12], to correctly predict the non-linear behaviour of the perforated panels. These factors are deduced with the purpose to fit the panel behaviour deriving from the cyclic curve envelope by means of a bilinear curve. Moreover, these design charts are valid in the case of panels having the same geometry and material of those considered in the parametric analysis. Additional developments are needed to extend the achieved results to other analysis cases.

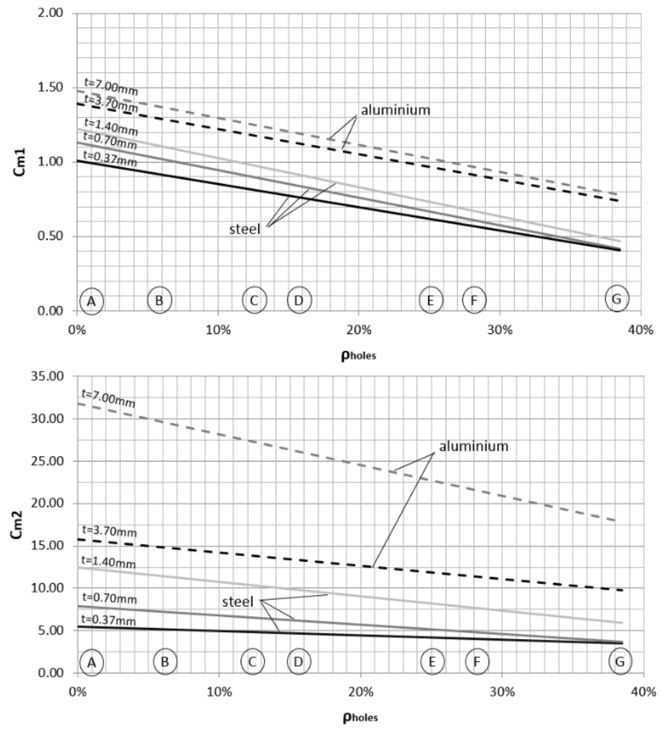


Figure 6. Design charts for estimating the modification factors C_{m1} and C_{m2} used to predict shear capacity and initial stiffness of perforated shear panels according to Equations (1) and (2).

6 CONCLUSIONS

The FEM study on unstiffened perforated shear panels have shown some relevant results. The available experimental results on panels with a central opening allowed to setup and calibrated an appropriate FEM model, where geometric imperfections and material non-linearity can be considered. This model can also take into account the presence of the bolted plate-to-frame connections and their imperfections. The proper calibration of the model allows to obtain a satisfactory numerical-to-experimental agreement in terms of the overall behaviour.

In this framework, a parametric FEM analysis on panels with different perforation patterns, material and thickness has been carried-out. The different perforation patterns have been considered by modifying disposition, number and diameter of the holes. Two types of material have been considered: steel and aluminium. From the results it is observed that, despite the presence of holes, the inclination of tension-field essentially remains to 45°. Comparing to traditional panels, the number of active bands decreases and it is reduced to one in the case of one centred hole. Furthermore, there is a different activation of the yielding mechanism with respect to traditional panels, where yielding is activated in corner zones penalizing the connection system. Contrary, for perforated panels, yielding activates around the holes, without stressing the system joints. Also, for perforated panels with a high percentage of holes, a considerable reduction of stress in the perimeter area is found. Furthermore, by adopting thicker perforated plates, very large drifts can be attained without failure around the holes. In conclusion, it has been shown that aluminium panels have a better dissipative behaviour, characterized by a more negligible pinching effect than in case of steel panels.

Finally, it has been shown that the use of conventional steel panels with different perforation patterns can be a viable alternative to the traditional panels for strengthening and stiffening both new and existing structures. In fact, if perforated panels are applied for example to an existing structure, by choosing an appropriate drilling configuration, it is possible to improve the resistance of the base building without aggravating the main structure with high stresses deriving from the tension-field generated by the plates. Therefore, perforated panels appears to be also more economic than the traditional plates, because the reinforcement interventions of the original building are lower in comparison to those required by traditional panels, due to weakening effect induced by the holes in the panels.

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