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Ductility and Behaviour Factor of RC Frame - Perforated SPSW Dual Systems

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Abstract. In this paper the non-linear behaviour of dual seismic-resistant structures made of Reinforced Concrete Frames (RCF) and perforated Steel Plate Shear Walls (SPSWs) has been investigated. The starting point has been the numerical calibration by ABAQUS of an experimental test taken from literature on one-third scale three-storey RCF with infill SPSWs subjected to monotonically increasing horizontal loading. Based on results of the implemented FEM model, three types of perforated SPSWs with different percentages and position of holes have been numerically analysed through static non-linear analyses. On the basis of numerical results achieved, by comparing each other the values of shear strength, behaviour factor and ductility of the tested specimens, it has been observed a significant improvement of the ductile behaviour of the RCF equipped with perforated SPSWs with respect to the one obtained for the RCF provided with traditional solid SPSWs. In addition, the dual systems given by RCF and perforated SPSWs have provided a shear strength reduction of 26%, 46% and 51% in comparison to that of the original RCF - solid SPSW composite system, when holes percentage equal to 13%, 40% and 42% have been considered, respectively. Finally, it has been noticed that behaviour factors of perforated specimens have been increased with increasing adjoining distance among holes.

Introduction

As indicated in the modern seismic codes, structures should be designed to minimise damages under medium earthquakes. SPSWs are one of the most effective methods introduced in the Seismic Engineering field to accomplish this result [1]. These seismic-resistant systems are achieved by inserting, through either welding or bolted connections, infill metal sheets within a boundary frame made of reinforced concrete or steel. The thin metal SPSWs are affected by buckling phenomena with larger out-of-plane deformations under horizontal loads and their resistance towards these lateral actions is guaranteed thanks a post-buckling shear behaviour [2]. Nowadays, one of the ways to reduce stresses around the main members of the boundary frame is to create holes in the area of metal panels [3]. The metal SPSWs with infill perforated thin plates have been investigated by many researchers, because they basically have the same stiffness of traditional full devices, while the ductility can be improved by placing appropriate holes on the plate surface. Recent earthquakes have shown that RC shear walls used as typical strengthening and stiffening devices of RC structures have presented shear cracking which, if large, are difficult and expensive to be repaired, especially when they appeared in combination to out-of-plane displacements of cracked parts of walls. What is more, the ductility and energy dissipation of RC shear walls cannot be increased to a level as high as those of SPSWs [4]. In fact, when RC structures are of concern, other than the most known typical retrofitting interventions, namely steel concentric and eccentric braces [5, 6], as well as buckling restrained braces [7, 8], the use of metal shear panels SPSWs can be profitably used as seismic upgrading devices to improve the performance of the base structure in terms of strength, stiffness and energy dissipation capability.

The lack of extensive literature studies on SPSWs for seismic retrofitting of existing RC framed structures has pushed from several years the research group of the University of Naples, leaded by the third Author of this paper, to undertake an extensive theoretical-numerical-experimental research on these devices. Such activities were finalised to both the retrofitting design of two-storey and eight-story Greek buildings [9, 10, 11] and the application of steel and aluminium SPSWs for increasing the seismic behaviour of a full-scale two-storey Neapolitan building, tested experimentally in the framework of the ILVA-IDEM research project [12, 13, 14, 15, 16, 17, 18, 19, 20].

More recently, the need of limiting the forces transmitted by metal plates to the surrounding frame members has required, as an alternative to the use of aluminium alloys, the employment of perforated steel plates, which have the benefit of experiencing excursions in plastic range already for low stress levels. Recent studies carried out by the Authors have shown the suitability of such panels for seismic-resistant applications through the setup of easy design tools useful for their application [21, 22, 23, 24, 25].

The current research activity is, therefore, framed as a natural continuation of the studies undertaken, with the aim of giving general validity to the design procedure developed in the past for seismic retrofitting of RC buildings using metal shear panels. In particular, after the numerical calibration of experimental tests performed on a RCF equipped with solid SPSWs, the attention is herein concentrated on the use of different types of perforated SPSWs as dual system of the main structure in resisting lateral actions, as described in the following Sections.

The Reference Experimental Tests

The experimental cyclic loading tests performed by Choi and Park [26] on several configurations of thin steel shear walls, used in combination to a RCF, have been considered as reference activities to calibrate an effective FEM model aiming at predicting the behaviour of the examined composite seismic system, as shown in the next Section. In the inspected tests, the seismic behaviour of a RCF with infilled SPSWs has been compared with that of a bare RCF without infills. Two mm thick steel shear walls connected to the RCF members by end plates with section of 100x12 mm have been employed as seismic devices. These end plates have been connected by two rows of studs (diameter = 13 mm and length = 150 mm) having intervals of 100mm.

According to the above experimental study, by assuming the tension field forces of steel infill plates uniformly distributed along the column length, the axial force (N_u), the bending moment (M_u) and the shear force (V_u) applied to the column in case of fully restrained ends can be provided by the following equations:

$$N_u = n_s \cdot h_s \cdot f_y \cdot t \cdot \sin\alpha \cdot \cos\alpha \tag{1}$$

$$M_u = \frac{1}{12} \cdot R_y \cdot f_y \cdot t \cdot h_s^2 \cdot \sin^2\alpha \tag{2}$$

$$V_u = \frac{1}{2} \cdot R_y \cdot f_y \cdot t \cdot h_s \cdot \sin^2\alpha \tag{3}$$

where n_s = number of stories; h_s = inter-story height; R_y = over-strength factor for the steel infill plate (equal to 1.3 for the used SS400 steel); f_y = design yield strength, t = thickness of the steel infill plate and α = inclination angle of the tension field (assumed to be 45° in the preliminary design phase).

According to the above formulas, the cross-sections of the columns, beams and top beam were 300 × 300 mm, 300 × 200 mm, and 300 × 300 mm, respectively, as shown in Fig. 1a.

Other than assessing the performances of the bare RC frame, in order to have a more comprehensive study, the benefits deriving from infill SPSWs on the behaviour of the RC frame have been also compared to those of the classical solution given by RC shear walls used for retrofitting purpose. The reinforcement details of used RC shear walls, having thickness of 11 cm, are depicted in Fig. 1b. Major details about rebars used for RC members are given in [26].

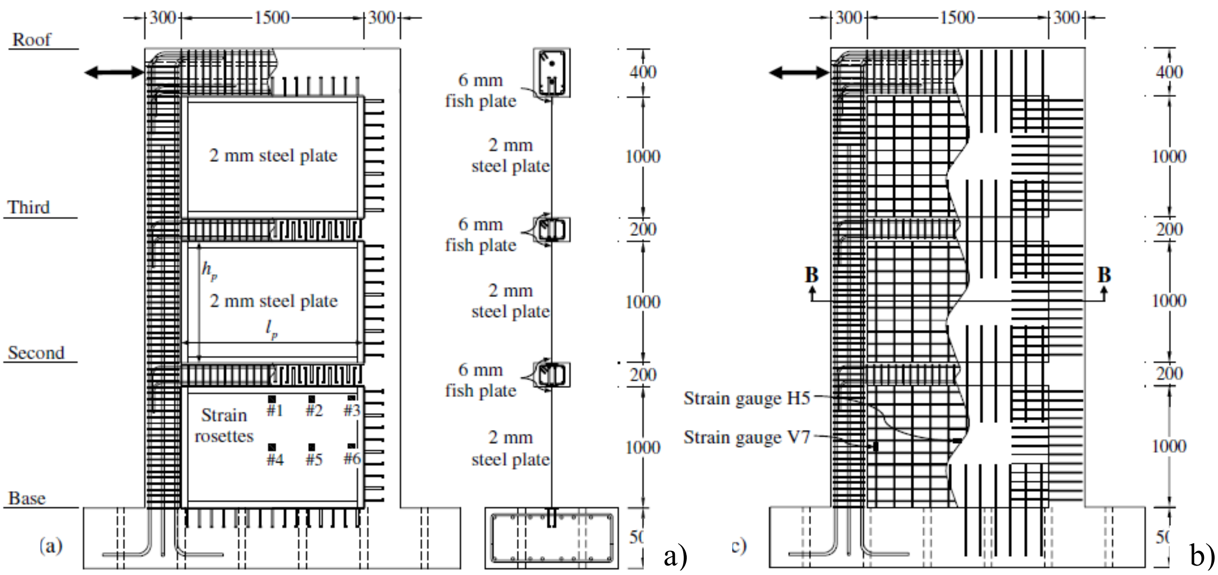


Fig. 1. Geometrical configuration of the RC frame retrofitted with SPSWs (a) and RC shear walls (b) [26]

For concrete the Poisson ratio and the Young modulus were equal to 0.15 and 25000 MPa, respectively. The concrete strength of frame members was 26.4 MPa, while for the shear wall was 32.1 MPa. On the other hand, for steel rebars, studs and infill plates, the Poisson ratio and the Young modulus were equal to 0.30 and 200000 MPa, respectively. Mechanical properties and some geometrical dimensions of steel members, connectors and seismic devices are illustrated in Table 1.

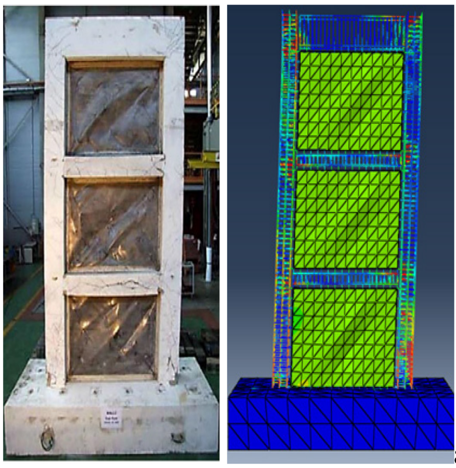
Table 1. Mechanical properties of steel members, connectors and seismic devices

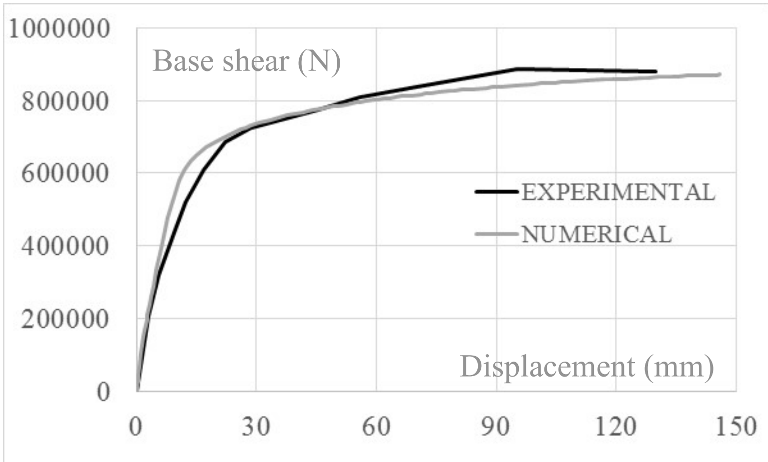
Element type	Dimensions [mm]		Yield stress [MPa]	Ultimate Stress [MPa]
Column rebars	Diameter	22-25	430-443	590
Beam rebars		16	471	590
Stirrups		10	486	590
Studs		13	240	370
End plates	Thickness	12	240	370
Infill panels		2	302	440

The RC frames equipped with the above anti-seismic devices were subjected to lateral cyclic tests through a hydraulic jack with loading capacity of 2000 kN applied to the top beam. No vertical loads were applied to the structures. The yield displacement δ_y at the structure top was estimated by numerical analysis to be equal to 15 mm. The target displacements for the cyclic loads were set as $\pm 0.2\delta_y$, 0.4 δ_y, $0.6\delta_y$, $0.8\delta_y$, $1.0\delta_y$, $1.5\delta_y$, $2\delta_y$, $3\delta_y$, $4\delta_y$, $6\delta_y$ and $8\delta_y$. These cyclic loads were repeated three times for each displacement. From the analysis results in terms of hysteresis curves, it was shown that the ductility and dissipation energy of the RC frame-SPSWs dual system were better than the bare RC frame ones. Moreover, the performances of infill steel shear walls were better than those of RC shear walls. However, despite the positive results derived from the use of steel shear panels for improving the seismic behaviour of the investigated RC framed structure, in order to reduce the demands required by steel plates to the RC frame members, it is necessary to study the beneficial effects of openings obtained by drilling the panel surface, as shown in the next Section.

Numerical Calibration of Experimental Results

The FEM modelling is a suitable approach to predict in a not too difficult way the behaviour of perforated SPSWs. To this purpose, the reference experimental tests of Choi and Parks before presented and discussed have been numerically simulated with the finite element simulation program ABAQUS [27]. Both concrete frame and foundation have been modelled with C3D4 brick elements. The frame has been joined to foundations through a surface to surface tie connection. Infill panels have been modelled by S4R shell elements, while linear truss elements have been used to model rebars. Tie connections have been used as constraints to model interactions between studs and end plates, as well as between end plates and SPSWs. Interaction between end plate and the surrounding frame members has been defined by hard contact and tangential behaviour, the latter with a friction coefficient equal to 0.2. Out-of-plane deformations have been avoided for top and middle beams by defined boundary conditions. According to the experimental evidence, the frame has been pushed laterally up to a displacement of 140 mm. The implemented FEM model, similar to that proposed by some of the Authors to calibrate the experimental results provided in [12-17], allows to obtain an excellent agreement with the test outcomes, as shown in Fig. 2. The same model is herein used for parametric analysis of the investigated RC frame equipped with perforated SPSWs having different patterns of holes.


a)



b)

Fig. 2. Experimental-numerical comparison in terms of final deformed shapes (a) and pushover curves (b) of the test performed by Choi and Park [26]

Parametric Analysis on Perforated SPSWs

In the current section, the performances of fourteen types of perforated steel shear panels under monotonic loadings have been numerically investigated. Three different sets of panel devices have been taken into account. The first set is made of eight panels (from SPSW1 to SPSW8 in Fig. 3) having an opening area equal to 13% of the total panel area. They are characterised by holes with diameter of 100 mm placed in different positions on the plate surface, as shown in Fig. 3.

The second set is represented by three panels (from SPSW9 to SPSW11 in Fig. 3) always having holes of 100 mm, but covering a total opening area equal to 40% of the total panel surface.

Finally, three panels with nine holes (from SPSW12 to SPSW14 in Fig. 3), having diameter of 300 mm and placed with different distances each other and from the panel ends, represent the third set of devices with perforation area equal to 42% of the plate surface.

The goals of investigating the second and third series of panels is to evaluate the effect of increasing the distance among adjoining holes, by decreasing at the same time the distance of holes from the shear panel edges.

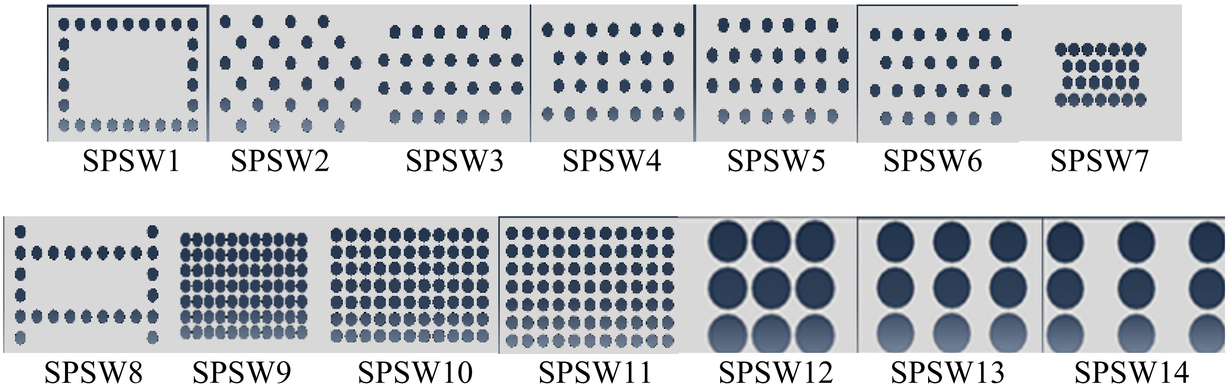


Fig. 3. Different patterns of holes on the surface of investigated panels

The above panel devices have been inserted within the same three-storey RC frame described in the previous Sections. For this reason, mechanical and geometrical properties of RC frame members, as well as boundary conditions, constraints, restraints and mesh type and dimensions adopted in the FEM model have been assumed as equal to those used in the experimental campaign performed by Choi and Park [26].

In the pushover analyses carried out, the Von Misses stresses and the out-of-plane displacements developed in the plates have represented the investigated parameters used to compare the performances of different perforated panel devices. In Fig. 4 these parameters have been illustrated for panels SPSW1 and SPSW2, inserted within the three-storey RC frame which has been deliberately eliminated from the graphic representation, at the end of the loading tests. Only these two panels have been herein examined in detail, since the observed stresses and displacement shapes are very similar to those manifested by other devices with holes percentage of 13%.

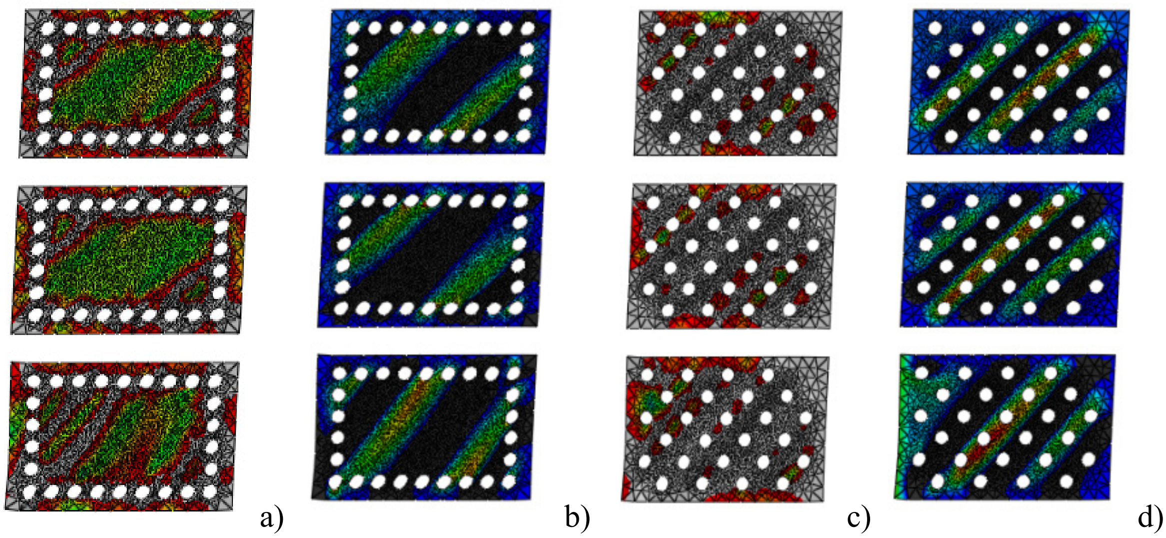


Fig. 4. Von Mises stresses (a, c) and out-of-plane displacements (b, d) detected for panels SPSW1 (boundary holes) and SPSW2 (diffused holes)

From the previous figure it is apparent that the two SPSWs have different behaviour under lateral actions in terms of both development of yielding zones and tension field inclination. In fact, the yielding distribution in the SPSW1 model is not widespread uniformly in the shear panel centre and the out-of-plane displacements corresponding to tensile diagonal bands are very pronounced.

On the other hand, for the SPSW2 panel the yielding distribution is more extensive on the plate surface. For this reason, the capacity of SPSW2 is more usefully exploited. The comparison among pushover curves achieved for the eight SPSWs with 13% of holed area is shown in Fig. 5.

On the other hand, by comparing the Von Misses stresses and out-of-plane displacements among perforated specimens SPSW9, SPSW10 and SPSW11 (40% of holed area), with adjoining distances of holes equal to 10 mm, 20 mm and 30 mm, respectively, it is noticed that the yielding distribution of SPWS10 is more uniform than that of the SPSW9 system. Also, in SPSW10 and SPSW11 the yielded parts and the out-of-plane displacements are very similar each other. In order to illustrate these outcomes, the pushover analysis curves on the above systems are shown in Fig. 6a. From these results, it can be seen that, by increasing the adjoining space among holes from 10 mm to 20 mm, the ultimate shear strength increases of about 7%, whereas this increment is of about 0.8% when panel portions among opening passes from 20 mm to 30 mm.

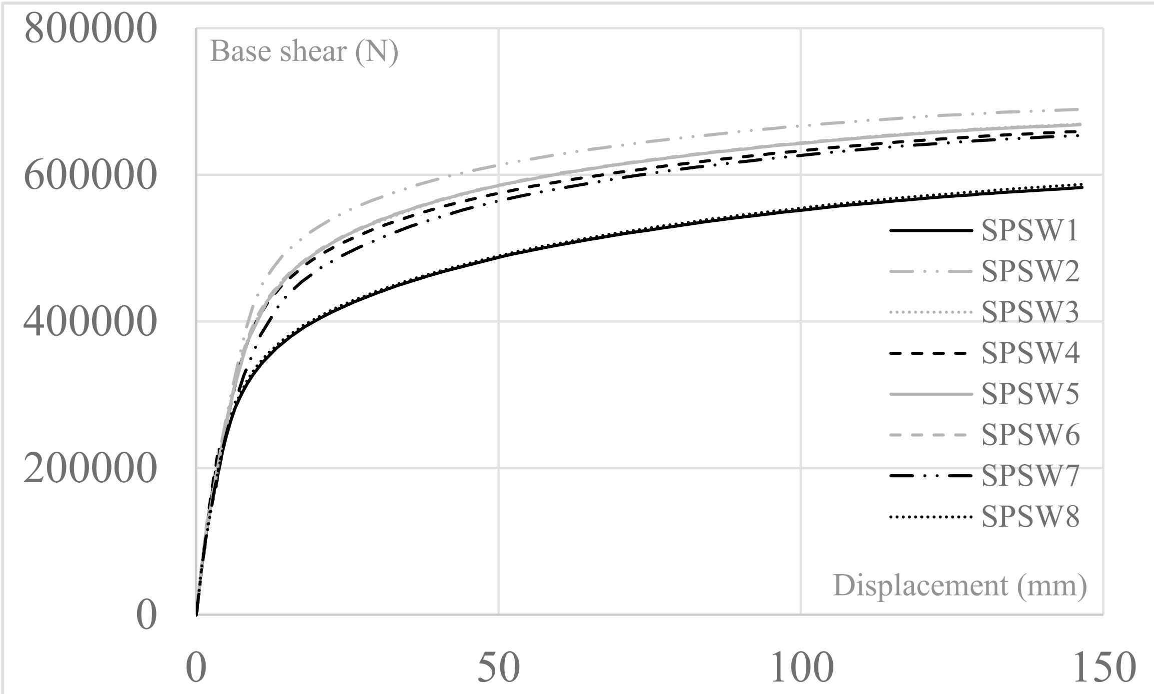


Fig. 5. Pushover curves of SPSW devices with 13% holed area

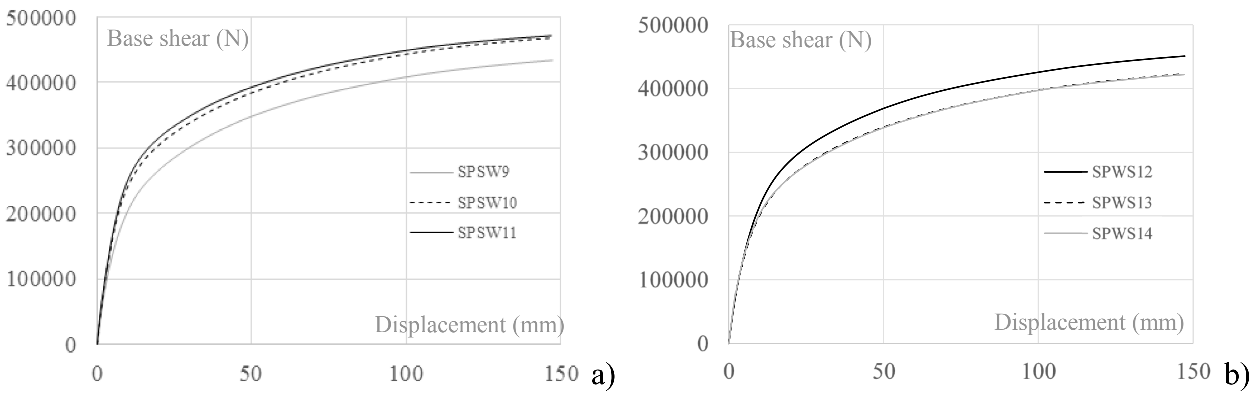


Fig. 6. Pushover curves of SPSW devices with 40% (a) and 42% (b) holed areas

Moreover, the comparison has been done among SPSW12, SPSW13 and SPSW14, having an opening area equal to 42% of the total plate surface, where the panel portions between two consecutive holes have lengths equal to 30 mm, 200 mm and 300 mm, respectively. As shown in Fig. 7, by reducing the distance among holes, the yielding distribution is always less accentuated. SPSWs having openings with distance from edges less than the distance among each other have the largest yielding zones. Fig. 6b compares the load-displacement curves obtained from the pushover analysis for these SPSWs.

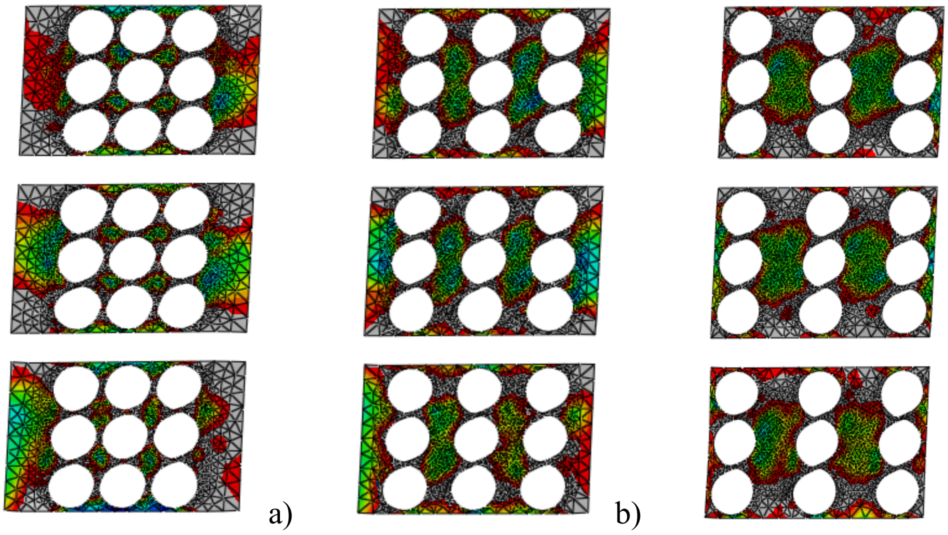


Fig. 7. Von Mises stresses detected for panels SPSW12 (a), SPSW13 (b) and SPSW14 (c)

Finally, the performances of examined SPSWs in terms of shear strength and ductility have been compared each other. As shown in Fig. 8a, the shear strength of specimens increases when perforation ratio decreases. Average values of ductility for SPSWs with 13%, 40% and 42% of opening areas are 13.56, 12.18 and 10.55, respectively. As it can be seen in Fig. 8b, the ductility factor of perforated specimens are significantly higher than that of the full panel $SPSW_{exp}$ experimentally investigated [26].

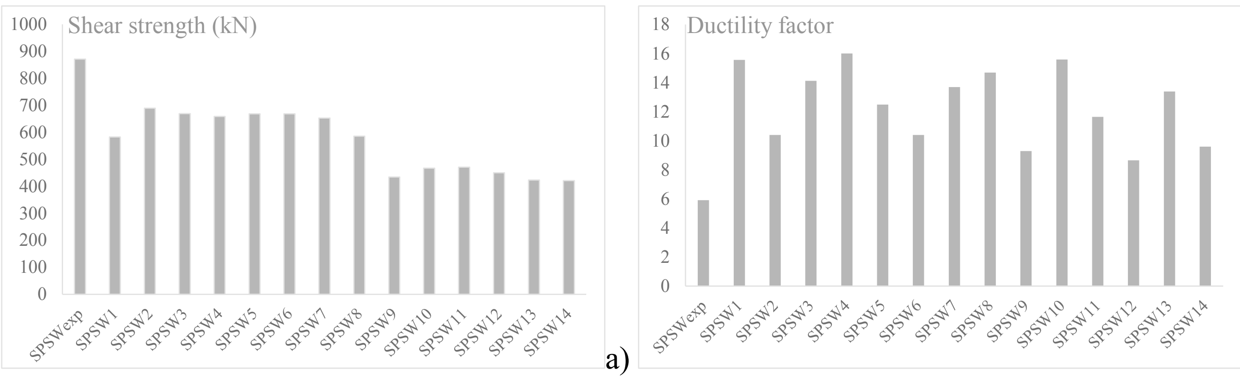


Fig. 8. Shear strength (a) and ductility factor (b) of inspected SPSWs

Behaviour factor evaluation

After numerical pushover analyses, the behaviour factors of examined SPSW specimens have been calculated according to the Uang's method [27] by using the following equation:

$$R = R_R \cdot R_\mu \cdot R_S \tag{4}$$

where R_R is the redundancy factor, assumed equal to 1 due to the high redundancy of SPSWs, R_μ is the ductility factor and R_s is the over-strength factor.

By simplifying the non-linear response curves of SPSWs through the bilinear elastic-perfect plastic ones, the ductility of structures can be estimated by the following relationship:

$$\mu = \frac{\delta_{max}}{\delta_y} \tag{5}$$

where δ_{max} is the maximum lateral displacement and δ_y is the yielding displacement.

SPSWs can dissipate a significant amount of the earthquake energy through a hysteretic behaviour due to ductility. Because of this energy dissipation capacity, the elastic design strength V_e can be reduced to the yield strength V_y. According to this, the ductility reduction factor R_μ can be estimated according to the following expression:

$$R_\mu = \frac{V_e}{V_y} \tag{6}$$

Aiming at estimating the ductility reduction factor, relationships have been proposed by different researchers [28, 29]. In this investigation, the formulation proposed in [29] has been used to estimate that factor for elastic-perfect plastic SDOF systems based on the following equations:

For f between 8 Hz and 33 Hz (period above 0.03 s but less than 0.12 s) $R_\mu = 1$ (7)

For f between 2 Hz and 8 Hz (period between 0.12 s and 0.5 s) $R_\mu = \sqrt{2\mu - 1}\ ;\ \frac{\mu}{R_\mu} \geq 1$ (8)

For f less than 1 Hz (period above 1 s) $R_\mu = \mu$ (9)

According to the above equations, the ductility reduction factor depends on period and ductility. Thus, modal analysis has been carried out for all specimens, whose frequency f has been estimated to be about 13 Hz. As a consequence, a ductility reduction factor equal to one has been taken.

The residual strength of structures after the formation of the first plastic hinge is called over-strength factor, which can be estimated as follows:

$$R_s = \Omega_0 = \frac{V_y}{V_s} \tag{10}$$

In Fig. 9 the comparison among behaviour factors of SPSW specimens is shown. In this figure, SPSW2, SPWS9 and SPSW12 have exhibited the lowest behaviour factors and the maximum shear strength within their categories. The reason can be attributed to the stress distribution on the area of these specimens, which is reduced when the distance among adjacent holes is little. In fact, as a consequence, the behaviour factor values from SPSW9 to SPSW12 are increased since the adjoining distance among holes is amplified.

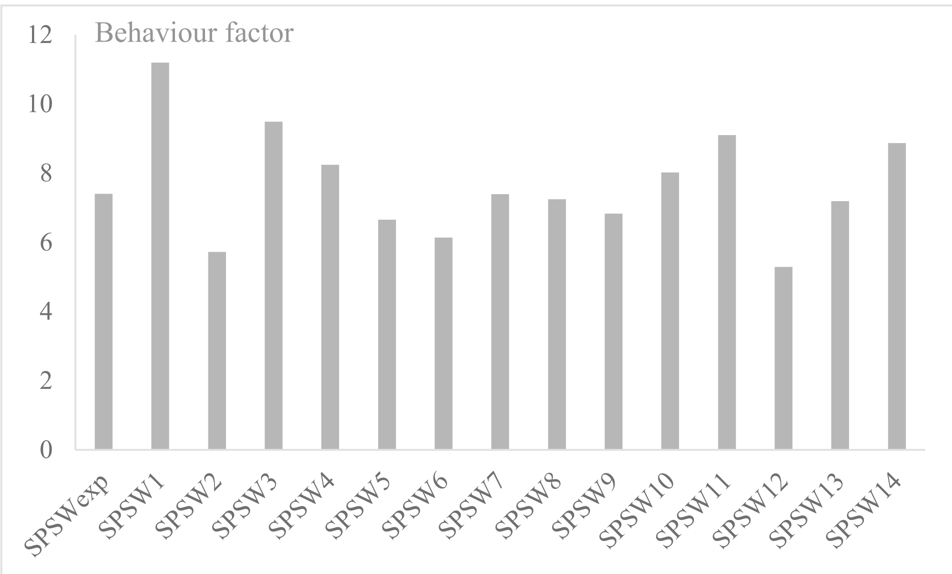


Fig. 9. Behaviour factors of inspected SPSWs

Finally, the achieved results have shown that, as also stated in [30], application of weakened SPSWs into RC structures is a useful method to improve, other than strength and stiffness, also their ductility, which allows for the attainment of high behaviour factors in some categories of examined perforated devices.

Conclusions

In this paper three different categories of perforated SPSWs with 13%, 40% and 42% of opening areas have been investigated as supplementary seismic-resistant systems into RCF structures. A parametric study by varying the placement and the diameter of holes on the surface of panels has been performed. The achieved results are summarised as follows:

- In 13% perforated SPSWs with holes concentrated around the plate edges, the shear capacity of the dual structure is lower than that of the same structure with openings distributed on the whole panel surface. Contrary, these SPSWs have shown the best ductility and behaviour factor in comparison to those of other inspected devices.
- As expected, the shear strength is greater for RCF-SPSW dual systems having panels with the lowest percentage of holes.
- By the comparison in terms of both stress distributions and pushover curves, it has been seen that SPSW models having reduced adjoining distance among holes exhibit a more diffused plasticization, but have a limited behaviour factor value.
- The greatest behaviour factors are noticed for dual structures with SPSWs having the largest distance among adjacent holes.
- The best ductility values are gotten when SPSW systems having the maximum distance among consecutive holes or the largest panel surface without holes are of concern.
- The ductility and behaviour factor values achieved by using perforated SPSWs are larger than those shown by the full SPSW with equivalent dimensions, which was experimentally tested in a literature paper taken as a reference for the calibration of the FEM model used for the numerical parametric study.
- Finally, the results deriving from the non-linear static analyses have proved that perforated SPSWs can be used, other than as strengthening and stiffening systems, also as very effective dissipative devices into dual structures in combination with RC frames.

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