STIFFNESS AND STRENGTH OF SPECIAL PERFORATED STEEL PLATE SHEAR WALLS ASSESSED WITH FINITE ELEMENT ANALYSIS

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Abstract

Special Perforated Steel Plate Shear Wall (SPSPSW) a is relatively new lateral force resisting system first introduced into to the 2010 edition of AISC 341. The special panel perforations are used to reduce the strength and stiffness of a solid panel wall to the level required in a design when a thinner plate is unavailable. This is beneficial to avoid excessive capacity design panel forces resulting in large boundary elements and foundations. Thicker perforated plates may also be preferred by contractors for easier transportation and handling than thin solid panels. Multiple holes are also convenient in allowing some utility lines and cables to pass through the web plate.

SPSPSW was proposed as an alternative design to some of the thinner panels in the solid Steel Plate Shear Walls (SPSW) on a base isolated office tower project located in Los Angeles. To understand the feasibility, Arup performed a series of comparative studies between solid and perforated SPSWs using ASCE equations and FE analysis of single bay frames and multiple bay / multiple level sub-assembly models.

The aim of the substitution of the thinner shear wall plates with thicker, perforated plates, was to match the stiffness and strength of the proposed perforated plates to the existing solid plates such that the change does not affect the global behavior of the building. The studies concentrated on the strength and stiffness comparison between the two systems and included detailed finite element shell models of both systems capturing explicit buckling and material non-linearity in the web plate using LS-DYNA. The main conclusion from the studies was that the stiffness of the perforated panels predicted by the detailed analysis is lower than the stiffness predicted by the AISC 341 equations. Another takeaway was that the size of perforations with the same perforation ratio does not significantly impact the behavior of the panels.

Based on the studies, the originally designed 1/8" thick solid plates were replaced with 3/16" thick plates with a 40% perforation ratio and 14" diameter perforations. This combination was analytically demonstrated to most closely match the strength and stiffness of the original wall panel. Additionally, a gradual increase in perforation ratio was used at a few floor levels from the solid panels in the lower half of the tower to 40% perforated at the top of the tower. This approach resulted in a smoother transition in panel strength and stiffness between floors, which minimized the impact on the horizontal boundary elements between the solid and perforated panels.

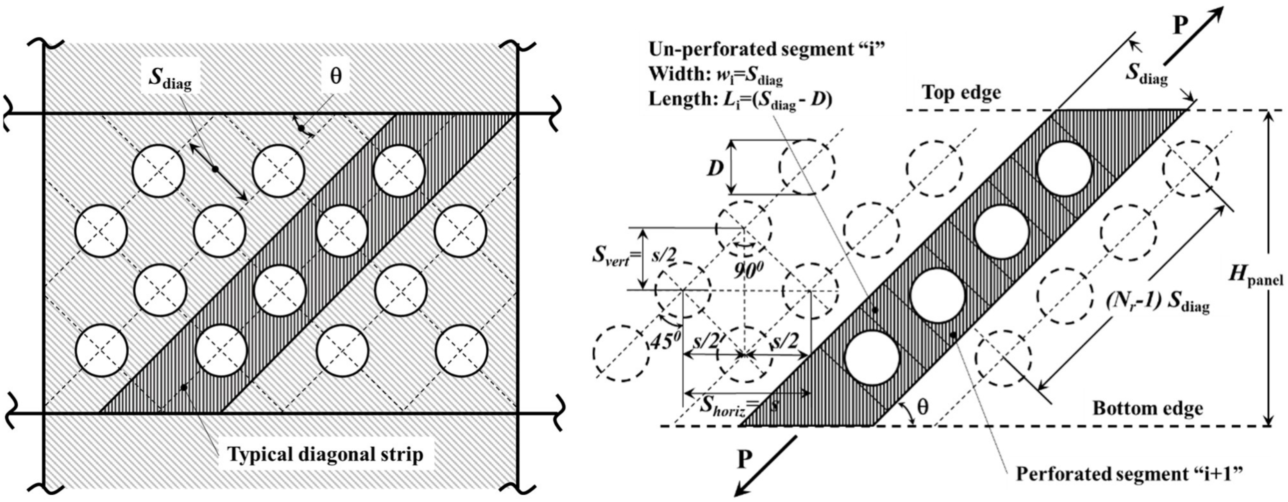
The project is currently under construction and when completed in 2022, it will become the first base isolated building with a SPSPSW in the world.

Keywords: Perforated Steel Plate Shear Wall, Performance Based Design, Finite Element Analysis, Building Codes, LS-DYNA

1. Introduction

Special Perforated Steel Plate Shear Wall (SPSPSW) is a relatively new lateral force resisting system first introduced into to the 2010 edition of AISC 341. The special panel perforations are used to reduce the strength and stiffness of a solid panel wall to the level required in a design when a thinner plate is unavailable. This is beneficial to avoid excessive capacity design panel forces resulting in large boundary elements and foundations. Thicker perforated plates may also be preferred by contractors for easier transportation and handling than thin solid panels. Multiple holes are also convenient in allowing some utility lines and cables to pass through the web plate.

The SPSPW concept has been analytically and experimentally proven to be effective (Vain and Bruneau, 2005 [1]; Purba and Bruneau, 2007 [2]; Vian et al., 2009 [4] [5]) and the approach codified in AISC-341 Article F5.7. Steel Plate Shear Walls (SPSWs) having a regular layout of circular perforations covering the entire web plate reduces the strength and stiffness of a solid panel wall to the levels required by design. A typical hole layout for this system is shown in Fig. 1.



(a) (b)

Fig. 1 – Typical hole layout (a) of special perforated SPSW and typical diagonal strip (b) (Vian 2005 [1])

Five variables define the panel perforation layout geometry: (1) D, the hole diameter, (2) S_{diag}, the diagonal strip spacing (measured perpendicularly to the strip), (3) N_r, the number of horizontal rows of perforations, (4) H_{panel}, the panel height, (5) θ, the diagonal strip angles. Horizontal and vertical spacing of circular holes can be easily estimated by trigonometry in terms of S_{diag} and diagonal strip angle θ.

SPSPSW was proposed as an alternative design to some of the thinner panels in the solid SPSW on a base isolated office tower project located in Los Angeles. The change consists of substituting 1/8" web plates with thicker, 3/16" perforated web plates and adding intermediate boundary elements to limit size of panels. To understand the feasibility, Arup performed a series of comparative studies between solid and perforated SPSWs. The aim of the substitution of the thinner shear wall plates with thicker, perforated plates, was to match the stiffness and strength of the proposed perforated plates to the existing solid plates such that the change does not affect the global behavior of the building. The studies concentrated on the strength and stiffness comparison between the two systems and included detailed finite element shell models of both systems capturing explicit buckling and material non-linearity in the web plate using LS-DYNA.

2. AISC 341 Provisions for SPSPSW

There are two limitations in AISC provisions for SPSPSWs [6] [8]. First, the holes regularly distributed across the web plate must be located in a grid that allows the development of continuous diagonal strips and filling the entire plate for yielding to spread along the length of those strips. For that reason, the first hole must be located at a clear distance of at least D but no greater than (D + 0.70 S_{diag}) from the web connections to the HBEs and VBEs. Second limitation is about the perforation ratio which is limited to 60%, $D/S_{diag} \leq 0.6$, as being the range addressed by past research.

2.1 Strength Reduction by Perforation

The design strength of a perforated web plate is codified in AISC 341 by below equation [6] [8].

$$\emptyset V_{np} = \emptyset\, 0.42\, t_{we}\, F_y\, L_{cf} \sin 2\theta \qquad \emptyset = 0.90 \tag{1}$$

Where, F_y is yield strength of web plate or strip, L_{cf} is clear distance between the VBE flanges, and t_{we} is effective web plate thickness due to perforation in terms of strength and expressed by the below equation.

$$t_{we} = \left(1 - 0.70\, {}^{D}/_{S_{diag}}\right) t_w \tag{2}$$

Where, t_w is web plate thickness, and D/S_{diag} is perforation ratio. Final form of shear strength with assuming perforated trip layout angle of θ=45^0.

$$\emptyset V_{np} = \emptyset\, 0.42 \left(1 - 0.70\, {}^{D}/_{S_{diag}}\right) F_y L_{cf} \tag{3}$$

Strength ratio due to perforation becomes.

$$V_{np} = \left(1 - 0.70\, {}^{D}/_{S_{diag}}\right) V_p \tag{4}$$

Where, V_{np} is strength of perforated web plate, and V_n is strength of solid web plate.

2.2 Stiffness Reduction by Perforation

Vian and Bruneau (2005) [1] [8] provided the following equation for estimating the reduction in panel stiffness due to presence of perforations.

$$\frac{K_{np}}{K_n} = \left[1 - \frac{\pi}{4}\left(\frac{D}{S_{diag}}\right)\right] \Big/ \left[1 - \frac{\pi}{4}\left(\frac{D}{S_{diag}}\right)\left(1 - \frac{N_r\, D\, \sin\theta}{H_{panel}}\right)\right] \tag{5}$$

Where, K_{np} is stiffness of perforated web plate, and K_n is stiffness of solid web plate. In addition to providing sufficient shear strength, the structure must also control inter-story drift to within the acceptable limits. A necessary component of this is establishing effective thickness of perforated web plates for stiffness. This is different from the effective thickness used in strength calculations.

The effective web thickness for stiffness is calculated as follows.

$$t_{we} = \left[1 - \frac{\pi}{4}\left(\frac{D}{S_{diag}}\right)/1 - \frac{\pi}{4}\left(\frac{D}{S_{diag}}\right)\left(1 - \frac{N_r\, D\, \sin\theta}{H_{panel}}\right)\right] t_w \tag{6}$$

3. Predictive Code Analysis for a Perforated One-Bay/One-Level System

A predictive analysis for a one-bay/one-level SPSPSW system was performed substituting 1/8" thick solid web plates with thicker 3/16" perforated web plates. The aim of the substitution of the thinner shear wall plates with thicker, perforated plates, is to match the stiffness and strength of the proposed perforated plates to the existing solid plates such that the change does not affect the global behavior of the building. Table 1 shows the equivalent web thicknesses using ASCE 341 for strength and stiffness due to perforation for a typical 3/16" thick web plate. With the perforation, the trend is a sharper decrease in strength than the decrease in stiffness. Matching perforated equivalent thickness (equal or smaller) for strength to 1/8" solid web thickness, will ensure no change in HBEs and VBEs. In order to match 3/16" thick perforated web plate for strength to 1/8" thick solid plate, 47.5% perforation is needed. Similarly, in order to match 3/16" thick perforated web plate for stiffness to 1/8" thick solid plate, 60% perforation (maximum allowed by the code) is needed (see Fig. 2).

Table 1 –Equivalent web thicknesses for strength and stiffness due to perforation for a 3/16" web plate

Equivalent Thickness & Ratio in		Perforation Ratio (D/S_{diag})						
		0%	10%	20%	30%	40%	50%	60%
Strength	in	0.1875	0.1744	0.1613	0.1481	0.1350	0.1219	0.1089
	Ratio	1.00	0.93	0.86	0.79	0.72	0.65	0.58
Stiffness	in	0.1875	0.1870	0.1830	0.1760	0.1630	0.1460	0.1260
	Ratio	1.00	1.00	0.98	0.94	0.87	0.78	0.67

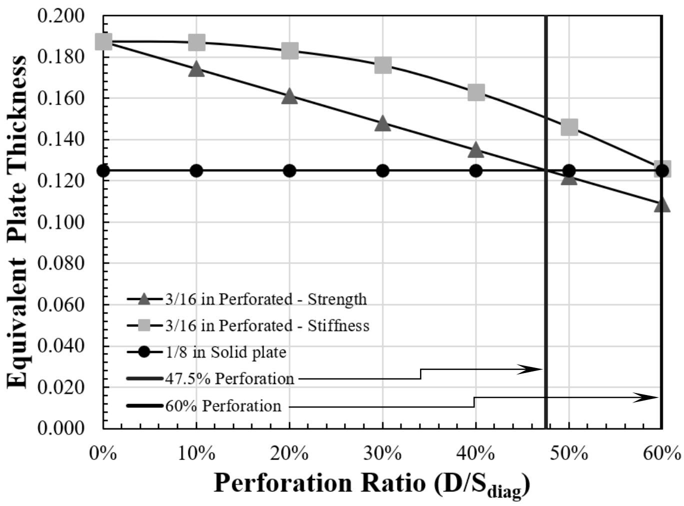


Fig. 2 – Reduction of strength and stiffness of a 3/16" web plate due to perforations.

Several hole diameters and respective perforation ratios were also investigated for a typical web plate height and width combination used in the project of interest (see Section 5). The results for a typical 3/16" thick 225in by 125in web plate with perforation ratios ranging from 10-60% compared to a solid 1/8" thick plate are summarized in Table 2 below.

Table 2 – Stiffness and Strength Reduction of 3/16" perforated (10-60%) web plates for a 225in x 125in bay

Width in	Height in	Nr -	D in	S_{diag} in	D/S_{diag} -	t_{we} Strength - in	Strength Ratio	t_{we} Stiffness - in	Stiffness Ratio
225	125	2	10	100	0.1	0.174	139.50%	0.186	148.60%
225	125	4	10	50	0.2	0.161	129.00%	0.180	144.10%
225	125	5	10	33.3	0.3	0.148	118.50%	0.173	138.20%
225	125	6	10	25	0.4	0.135	108.00%	0.163	130.20%
225	125	7	10	20	0.5	0.122	97.50%	0.150	120.00%
225	125	9	10	16.7	0.6	0.109	87.00%	0.130	103.90%

In summary, by replacing 1/8" solid web plates with 3/16" thick 60% perforated plates, the strength reduces 13% while stiffness increases only up to 3.9% (see last row in Table 2). Theoretically, similar perforations and structural performance can be achieved with different sets of hole diameter and number of rows. Fig. 3 shows the relationships between hole patterns and perforation ratios. To be more specific, if the perforation ratio is kept the same, the change in hole diameter and number of row sets, will not affect the equivalent strength. Equivalent plate stiffness my slightly change with the change in hole diameter. This is due to the geometry of the web plate and edge clearance requirements, but this is minimal. In summary, using different sets of hole diameter and number of holes at different floor levels are also feasible.

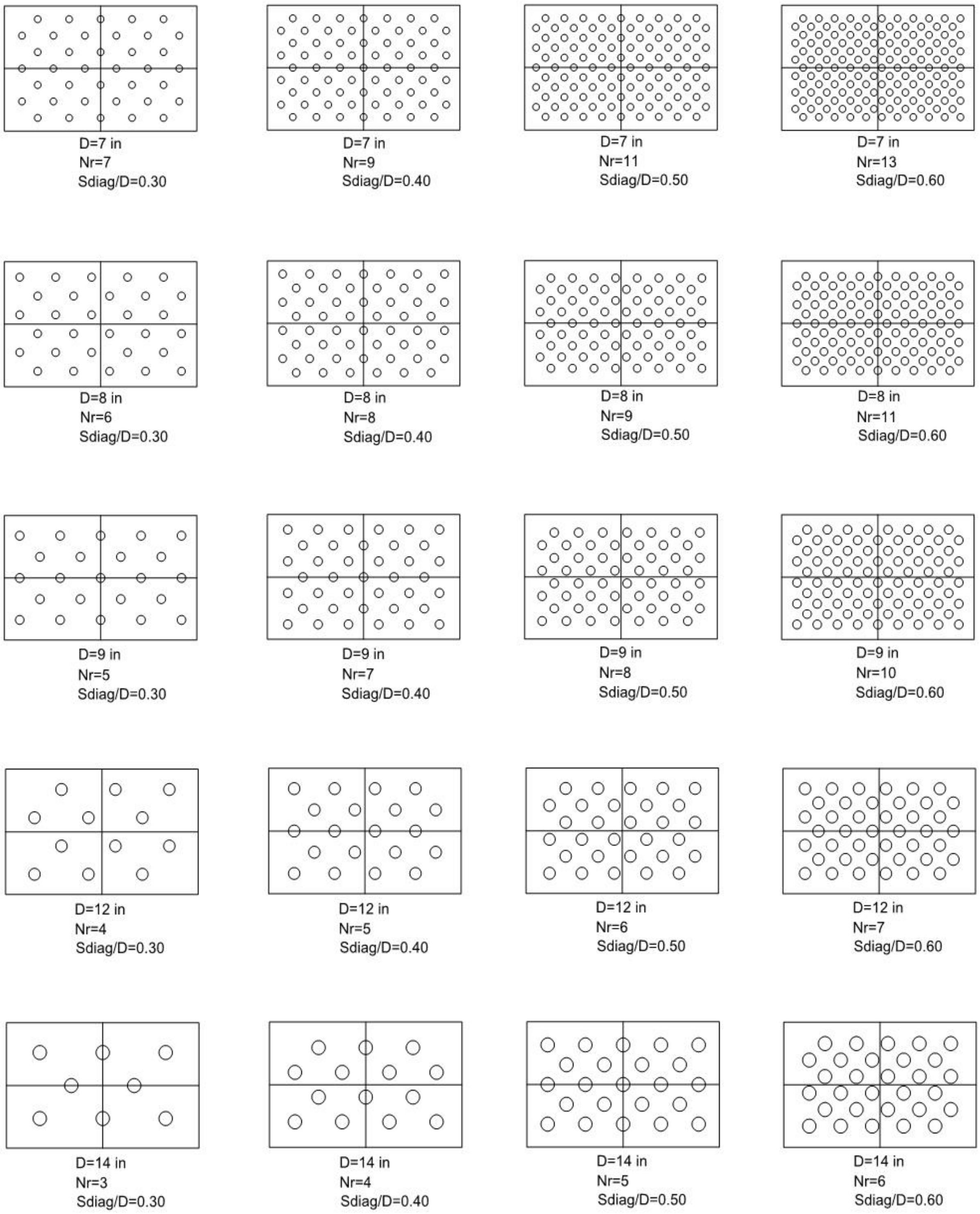


Fig. 3 – Relationship between hole patterns and perforation ratios for a typical 225 in by 125 in web plate

4. Nonlinear Analysis in LS-DYNA for a One-Bay/One-Level Sub Assembly

A series of LS-DYNA [7] nonlinear pushover analyses were performed to understand the behavior of the perforated panels at the geometry and with the section sizes used in a typical project. Resulting stiffness was compared at four inter-story drifts: 0.25%, 0.5%, 0.75% and 1%. Detail of the modelling approach is illustrated in Fig. 4.

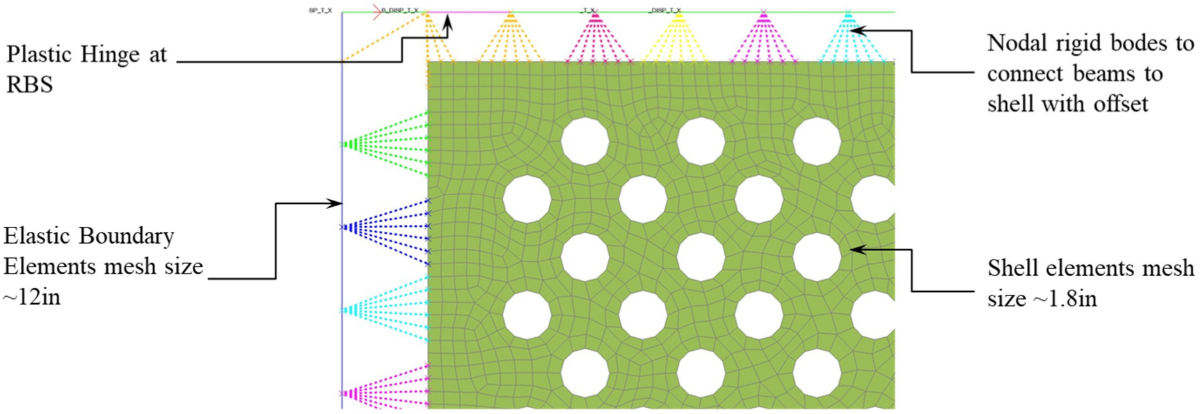
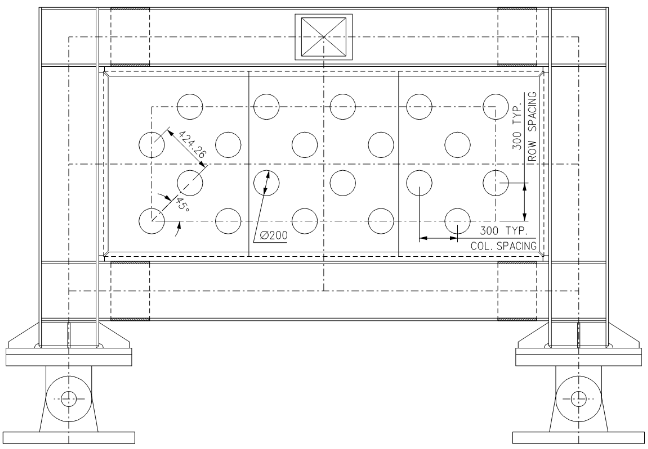


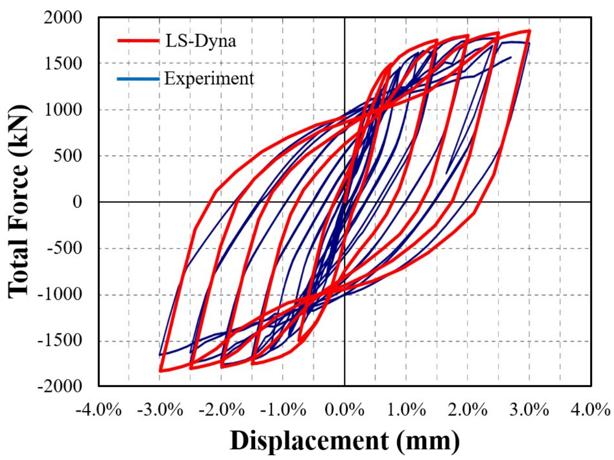
Fig. 4 – Quarter FE model of the perforated SPSW capturing both yielding and buckling of the members.

3.1 Nonlinear Model Calibration

The nonlinear modeling for the proposed perforated SPSWs and boundary frames were compared and calibrated with a cyclic physical experiment performed by Vian [2]. The test specimen is a half scale portal frame with a perforated 2.6 mm (1/10 in) thick web plate. The perforation diameter is 200 mm (8 in) and holes horizontally spaced 300 mm (12 in) at center. There are four horizontal rows at the specimen which is equivalent to a 47% perforation ratio. Fig. 5 shows the perforated SPSW specimen for the test and comparisons of hysteresis response curves. A very good agreement was observed between the hysteresis response curves obtained from the experiment and from nonlinear cyclic simulation using LS-DYNA [7]. Therefore, we were comfortable using a similar analytical approach for the parametric investigation for the Tower SPSPSW.



(a)



(b)

Fig. 5 – Perforated SPSW test specimen (a) and comparison of hysteresis response curves (b)

3.2 Effects of Panel Size and Perforations

A comparison of performance (strain and drift) was done for an 1/8" thick solid web plate and 3/16" thick perforated web plates with different perforation ratios using two typical panel geometries in the tower, see Fig.

6 and 7. The analysis shows that the stiffness and strength of a solid 1/8" plate falls in between 40% and 50% perforations in a 3/16" plate.

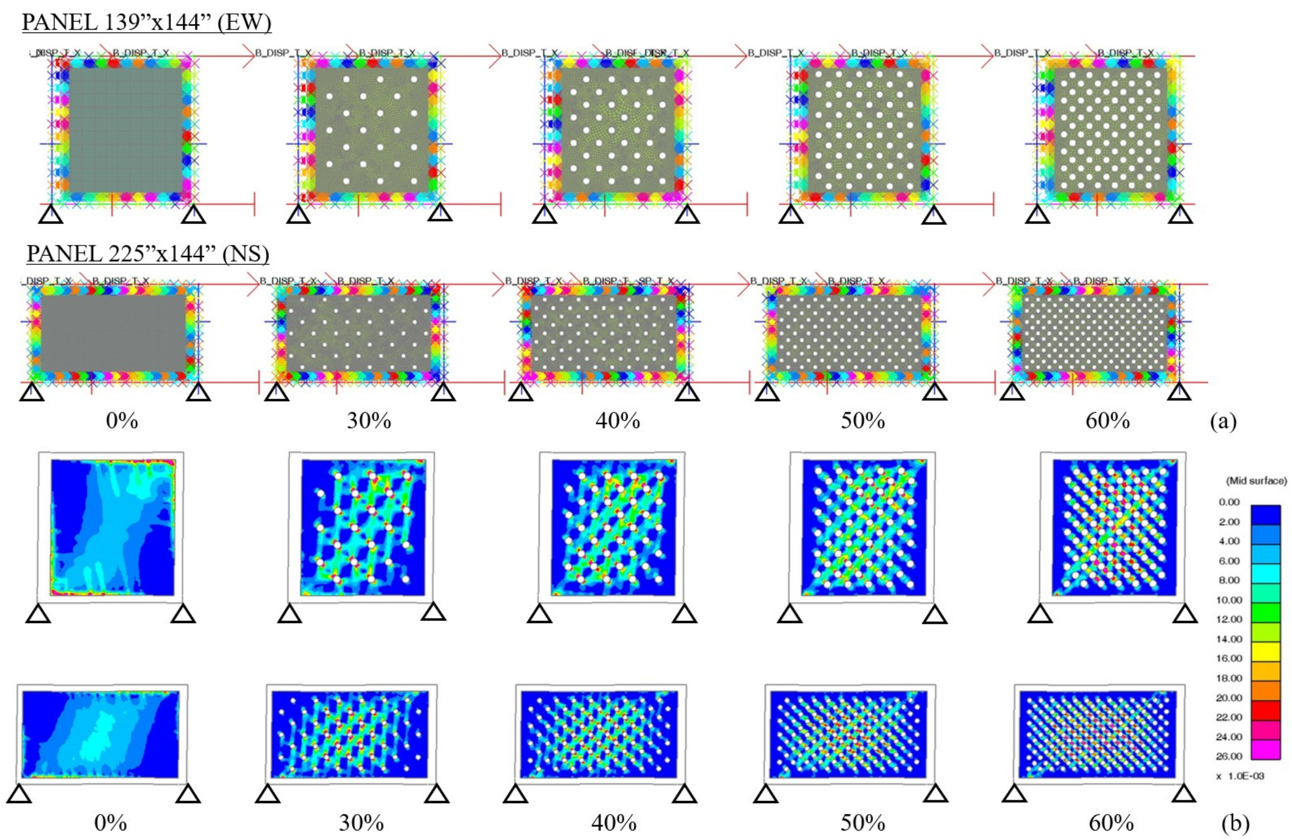


Fig. 6 –LS-DYNA models of two panels with increasing quantity of 7in (hole dia) perforations. Geometry above, strain distribution below.

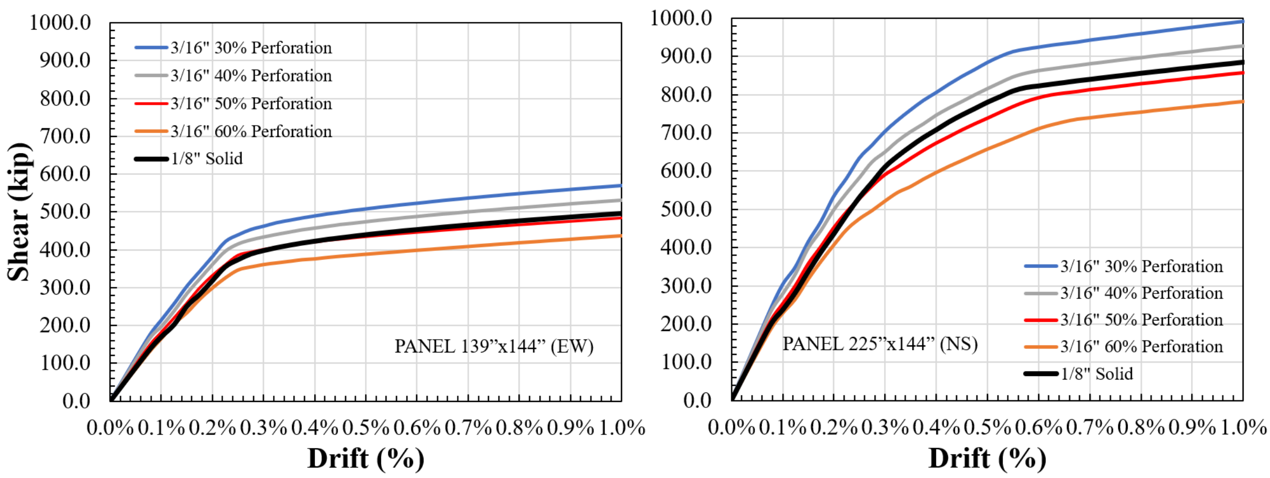


Fig. 7 – Pushover of a single panel with various perforation ratios

3.3 Effects of Perforation Size (Hole Dimeter)

A parametric analysis was performed for a typical panel to investigate the effects of change in hole diameters from 6" through 14" while holding constant perforation ratio. Model images are shown at Fig. 8 below.

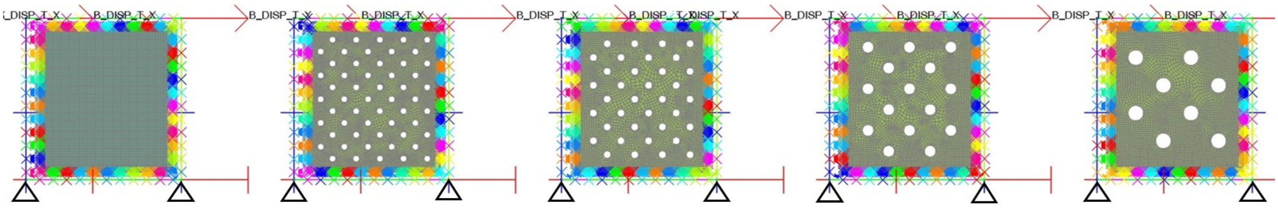


Fig. 8 – LS-DYNA model of a panel with 40% perforation ratio with holes varying from 6”to14” in diameter

The panels were subjected up to 1% racking drift pushover analysis. Fig. 9 shows that the behavior of the 3/16” perforated panels exhibit insignificant change with the hole sizes at the same perforation ratio.

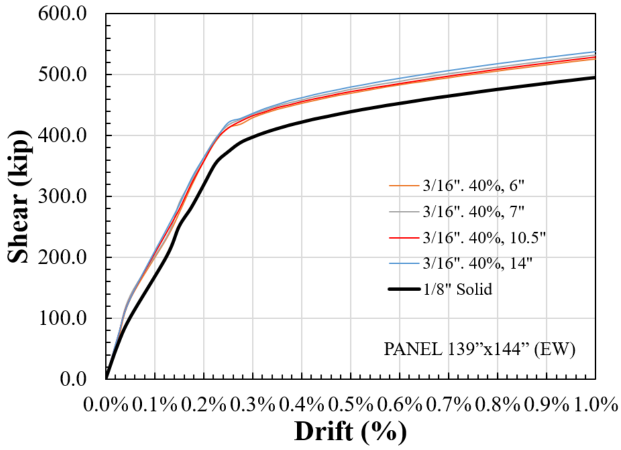


Fig. 9 – Pushover of a single panel with 40% perforation ratio with holes varying from 6”to14” in diameter

In summary, the findings from the parametric, FE, single panel studies are that: (1) The stiffness of the panel determined by FE analysis is lower than the stiffness predicted by the AISC 341 equation. (2) The size of perforation does not impact the behavior of the panels.

3.4 AISC Equation vs. LS-DYNA Analysis Results for Equivalent Plate Thickness

The effective panel web thickness (single panel) for stiffness based on the AISC equation is compared with the results from a nonlinear FE simulation done in LS-DYNA. The stiffness of the panel from FE analysis is lower than the stiffness predicted by the AISC 341 equation. See Fig. 10 for comparisons of equivalent plate thicknesses and varying perforation ratios.

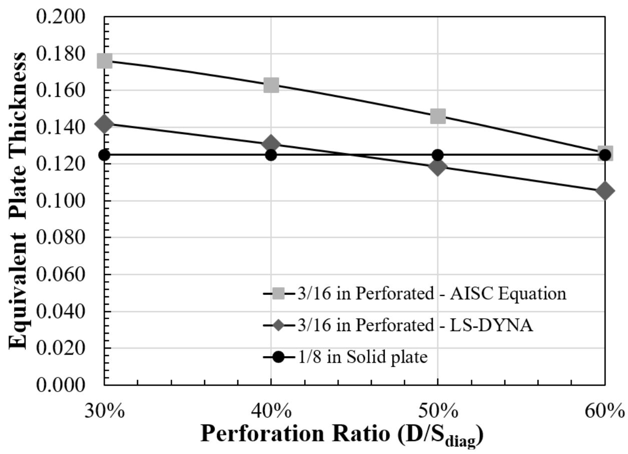


Fig. 10 – Equivalent web plate thicknesses per the AISC 341 equations and LS-DYNA analysis

The LS-DYNA analysis yields a roughly 16% stiffer plate for a 3/16" plate with 30% perforations than a solid 1/8" thick plate, and a roughly 16% less stiff plate for a 3/16" plate with 60% perforations than solid plate. Figure 10 demonstrates that a perforation ratio of roughly 45% in a 3/16" thick plate matches most closely to the original solid 1/8" thick plate. This approximately 80% of the equivalent plate thickness suggested by AISC 341.

5. Multi-bay/Multi-level Assembly – (W)rapper Tower

To further understand the behavior of perforated shear plate walls, as compared to solid, thinner plate shear walls, multi-bay, multi-level FE models were built and analyzed. The geometry for the SPSW core in (W)rapper Tower, a 16 story, 240ft tall building located in Los Angeles, California, was used [9] [10] [11]. The gravity framing of the regular office floors is composed of typical steel-concrete composite floor system supported by external, curved, structural Steel Bands with no internal columns. Selected 8 external bands run continuously to ground floor level. At ground level, the bands are supported by seismic isolators anchored to reinforced concrete columns to the foundation. Horizontal tie members (beams) at ground level are used to resolve the axial forces of the curved tower bands to vertical and horizontal forces. Bands that are not used to support primary floor members are connected to the floor diaphragm for lateral bracing. Perforated SPSW eccentric core on the south side of the building houses vertical transportation, MEP rooms and restrooms. An additional escape route is provided by means of an external staircase located on the east face of the building.

The lateral force-resisting system of the Tower consists of base isolators, a special perforated SPSW core, steel bands and trussed steel framing diaphragms at each level. The perforated SPSW consist of plates (web plate), boundary elements, gravity framing and concrete floors. Seismically Base isolating the Tower reduced the lateral demand by factor of 4. In the east-west direction (longitudinal), the SPSW core and the Bands resist approximately 40% and 60% of the total seismic shear respectively. In the north-south direction (transverse), the SPSW core and the Bands resist approximately 90% and 10% of the total seismic shear respectively. The contribution of the SPSW core and the Bands varies along the height of the tower. The Tower is seismically isolated on 60 in diameter Triple Friction Pendulum (TFP) bearings located under the Bands and SPSW core columns at the ground level. There are total of 18 isolators. The bearings are supported on concrete columns and supported on a 6 ft to 8 ft thick mat foundation. There is a moat around the perimeter of the Tower at ground level to accommodate movement of the isolated Tower structure. 3D Isometric view of the (W)rapper Tower LS-DYNA analysis model is shown at Fig. 11.

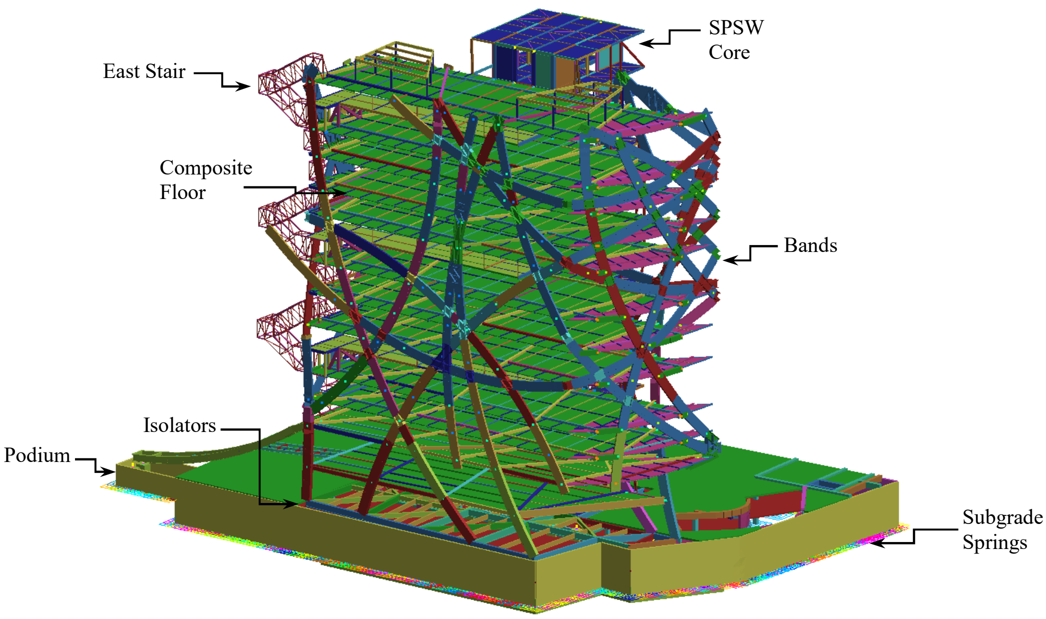
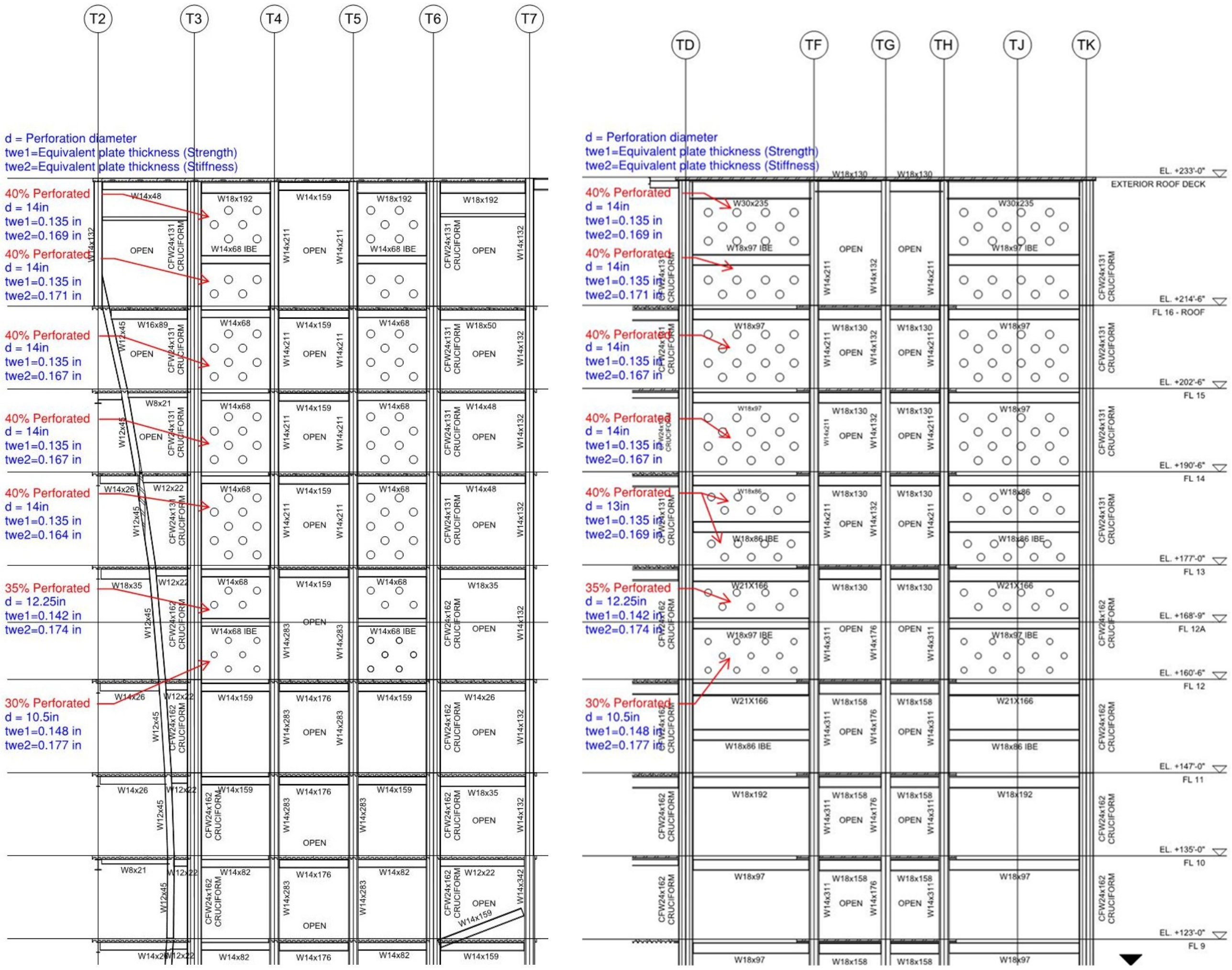


Fig. 11 3D Isometric view of the LS-DYNA analysis model of the (W)rapper Tower [9]

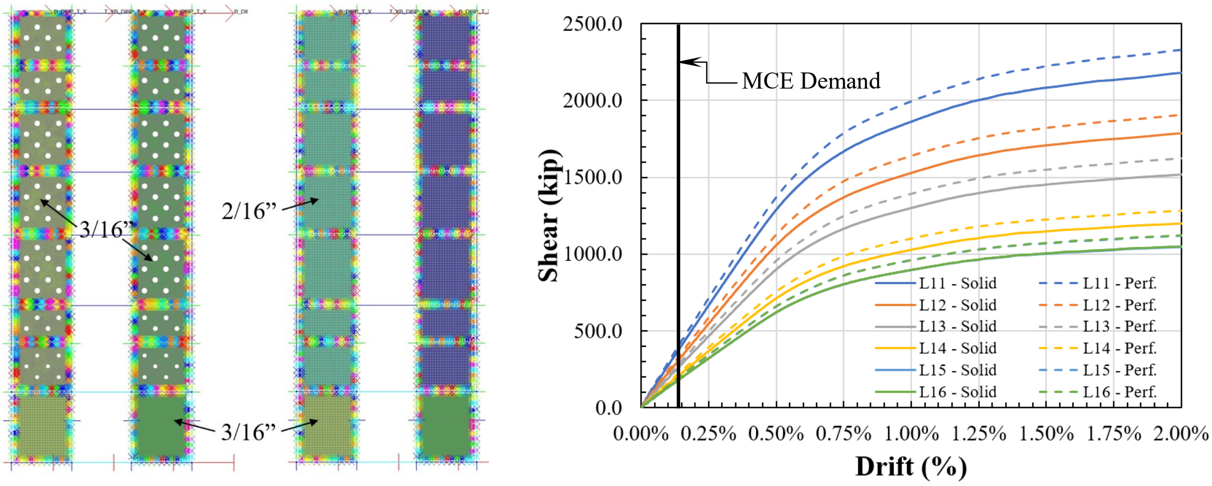
Based on the initial study results, a perforated wall panel layout with 14” diameter holes and 40% perforation were selected for the multi-bay/multi-level sub-assembly analysis. Additionally, a gradual increase in perforations was used at the bottom few stories to smooth the transition in panel strength/stiffness and minimize the impact on HBEs between perforated and solid panel (See Figure 12)



(a) (b)

Fig. 12 – Selected perforation pattern for SPSWs along Tower height at (a) EW and (b) NS directions.

The multi-story/multi-bay LS-DYNA pushover analyses were performed aiming to demonstrate that the stiffness of the perforated SPSWs, with the effect of boundary elements and coupling beams, is comparable to the original design with 1/8” solid web plates, and specifically within the range of demand anticipated for this building. In addition to that, the behavior of the frames in these sub-assembly studies was compared to the behavior and conclusions from the one-bay/one-level sub-assembly studies. The model of the one face of the core from Level 11 to the Roof (see Fig. 13) was subjected to story forces calculated from the envelope of MCE story shear. The MCE forces were gradually increased to wall failure (see Fig. 14). The LS-DYNA nonlinear pushover analyses were done using bi-linear steel with hardening material properties (*MAT_PIECEWISE_LINEAR_PLASTICITY). The results of these analyses showed that the stiffness ratio between the perforated and the solid walls were ranged between 105% to 115% at MCE demands (largest stiffness ratio happens at Story 12 where the perforation ratio reduces to 30%). Overall the stiffness was lower than the stiffness predicted by ASIC 341 equations in Table 3, which further confirms the findings from Section 4. The stiffnesses were approximately 80% of the equivalent plate thickness per stiffness suggested by AISC 341. The strength of the of the perforated SPSW exceeds the original design with solid web plate. The stiffness increases locally by 10% to 38% in NS direction and 5% to 15% in EW direction. The global overall building stiffness increases by less than 4% in either direction, NS and EW, therefore the slightly stiffer perforated steel plate web will have a negligible impact on the overall building performance.



(a) (b)

Fig. 13 – FEA model (a) in EW direction and (b) comparisons of pushover curves

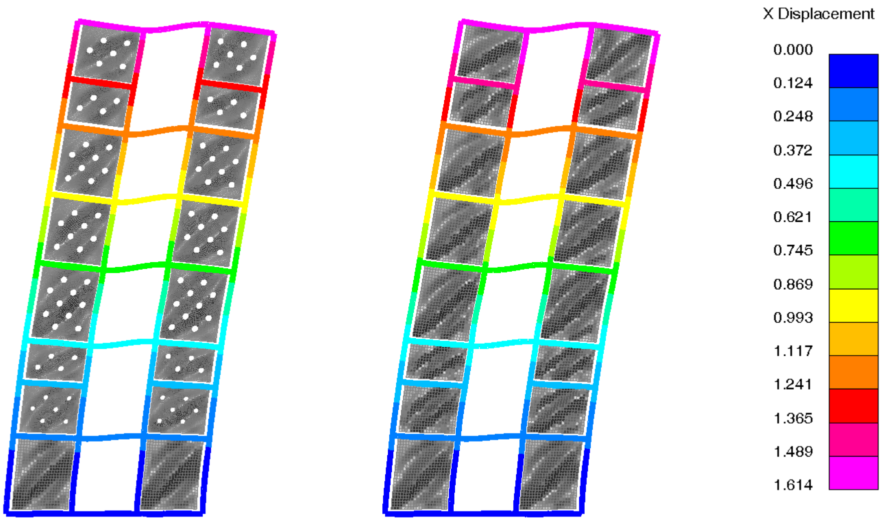


Fig. 14 – Wall displacement (100x magnified) at MCE demands – perforated SPSW (proposed, left) and solid SPSW (original, right).

Table 3 – Summary of results from EW Multi-story pushover analysis

STORY	MCE Demands			1.0% Roof Drift (D = 10.3")			Code Based Stiffness
	Solid Drift %	Perf. Drift %	Stiffness Ratio	Solid kip	Perf. kip	Stiffness Ratio	
ROOF	0.18	0.18	105%	896	960	107%	135.6%
STORY16	0.17	0.16	106%	896	960	107%	133.2%
STORY15	0.17	0.16	107%	1027	1100	107%	133.2%
STORY14	0.18	0.16	109%	1299	1392	107%	131.6%
STORY13	0.14	0.12	115%	1527	1639	107%	139.4%
STORY12	0.10	0.09	103%	1861	1995	107%	141.3%

6. Concluding Remarks

The special panel perforations are used to reduce the strength and stiffness of a solid panel wall to the level required in a design when a thinner plate is unavailable. This is beneficial to avoid excessive capacity design panel forces resulting in large boundary elements and foundations. Thicker perforated plates may also be preferred by contractors for easier transportation and handling than thin solid panels. Multiple holes are also convenient in allowing some utility lines and cables to pass through the web plate.

This paper aimed to study the strength and stiffness between the two systems by finite element analysis by capturing explicit buckling and material non-linearity in the web plate using LS-DYNA. The main conclusion from the studies was that the stiffness of the perforated panels predicted by the detailed analysis is lower than the stiffness predicted by the AISC 341 equations. Another takeaway was that the size of perforations with same perforation ratio does not significantly impact the behavior of the panels. Arup used sub-assembly models with various geometries and analysis methods to compare to results from the code-based design approach and determine the appropriate replacement for a 1/8" thick solid steel plate. Based on these studies, the originally designed 1/8" thick solid plates for the (W)rapper Tower were replaced with 3/16" thick plates with a 40% perforation ratio. This combination was analytically demonstrated to most closely match the strength and stiffness of the original wall panel. The authors suggest further research to study in-depth the reason for the difference in the stiffness prediction by the codified equations. The project is currently under construction and when completed in 2022, it will become the first base isolated building with a SPSPSW in the world.

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