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# A Direct Strength Method (DSM) of Design for Channel Sections in Shear with Square and Circular Web Holes

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# A Direct Strength Method (DSM) of Design for Channel Sections in Shear with Square and Circular Web Holes

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## Abstract

The Direct Strength Method (DSM) design rules for cold-formed steel members in shear have been incorporated recently into the North American Specification (AISI S100-12) and are being implemented in the Australian standard (AS/NZS 4600:2005). The method, which was calibrated for unperforated members only, requires two inputs including the buckling load $V_{cr}$ and the shear yielding load $V_y$. For members with square web cut-outs, $V_{cr}$ can be computed by either the Spline Finite Strip Method (SFSM) or the tabulated values based on the shear buckling coefficients $k_v$ as studied by CH Pham or the Finite Element Method (FEM). However, $V_y$ has not been accurately formulated including holes.

This paper represents a practical model to obtain $V_y$ for members with central openings subjected to predominantly shear. The model ranges from very small holes where traditional shear yielding predominates to large holes where Vierendeel action dominates. The model is verified with the DSM design formulae using the predominantly shear tests recently conducted at the University of Sydney and Queensland University of Technology with both square and circular web openings and for shear spans with aspect ratios of 1.0.

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## INTRODUCTION

In flooring systems, high strength steel cold-formed channel section beams are commonly used. Joist webs are often perforated as shown in **Fig. 1** to provide space for service systems which go through the webs to increase the floor clearance height and reduce the material cost. The presence of the web holes affects both the buckling capacities and strengths of structural members.

**Fig. 1.** Perforated light gauge beams (Bone Structure, 2005)

Members in compression and flexure with evenly spaced web holes have been studied in detail by Moen and Schafer (2010, 2011). The common cold-formed steel limit states which include local, distortional and flexural- torsional buckling for members with holes were addressed and the DSM design rules were also standardized in the North American Specification AISI S100-12 (AISI, 2012). For unperforated members subjected predominantly to shear, DSM design rules were also included in the AISI S100-12 based on the research by Pham and Hancock (2012a). However, for perforated members in shear, both the AISI S100-12 and the Australian Standard AS/NZS 4600:2005 (Standards Australia, 2005) still adopt an empirical approach based on the experimental research by Shan et al. (1994), Schuster et al. (1995) and Eiler (1997). The method allows the shear strength of a member with holes to be determined as a fraction of the strength of the unperforated member via the reduction factor $q_s$ computed as following:

When $c/t \geq 54$, $\quad q_s = 1 \qquad (1)$

When $5 \leq c/t < 54$, $\quad q_s = c/(54t) \qquad (2)$

where $c = h/2 - d/2.83$ for circular holes

$c = h/2 - d/2$ for non-circular holes

h is the depth of flat portion of the web measured along the plane of the web, t is the web thickness, d is the depth of web hole

As a result, it is not necessary to determine the buckling capacity $V_{cr}$ and the shear yielding load $V_y$ for perforated sections. Despite the computational convenience, the method was proved to be conservative for lipped channel sections with small web openings while unconservative for sections with large openings (Keerthan and Mahendran, 2013). In addition, the above reduction expressions are only applicable to a certain range of web opening sizes, presumably due to the limited number of experiments.

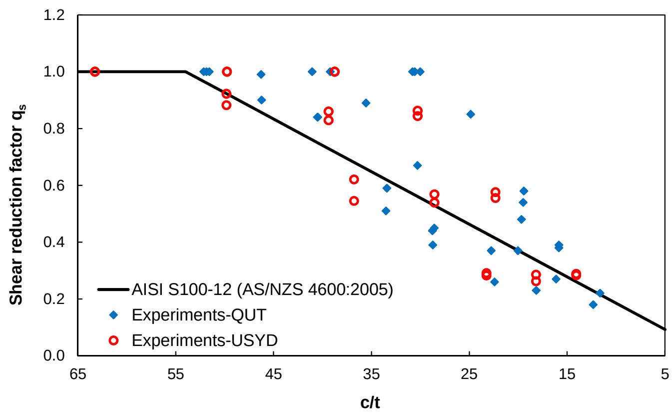



**Fig. 2.** Shear reduction factor comparison between tests and standards

In **Fig. 2**, the experimental data on cold-formed channel section members with aspect ratio (shear span / section depth) of 1.0 conducted by Pham et al. (2014, 2016) at the University of Sydney (USYD), Keerthan and Mahendran (2013) at Queensland University of Technology (QUT) has been used for comparison. The former test program used 200 mm deep channel members with different thicknesses including 1.5 mm, 1.9 mm, 2.4 mm and ***square*** opening sizes ranging from 40 mm to 120 mm. Meanwhile, the latter experimental program worked with a wide range of C-section dimensions (the web depths include 120 mm, 160 mm and 200 mm), various ***circular*** opening sizes and included tests on low-strength specimens as noted where applicable. These data sets are employed throughout the paper to verify the proposed model. In all the tests, full tension field action (TFA) is deemed to be reached. Therefore, all the related graphs hereafter disregard the DSM curve without TFA.

Keerthan and Mahendran (2014) proposed new empirical equations to determine the shear reduction factors that rely on the ratio of the circular web opening depth (D) to the clear web height ($b_1$) as following:

When $0 < \frac{D}{b_1} \leq 0.30$, $$q_s = 1 - 0.6\left(\frac{D}{b_1}\right) \quad (3)$$

When

$0.30 < \frac{D}{b_1} \leq 0.70$, $$q_s = 1.215 - 1.316\left(\frac{D}{b_1}\right) \quad (4)$$

When

$0.70 < \frac{D}{b_1} \leq 0.85$, $$q_s = 0.732 - 0.625\left(\frac{D}{b_1}\right) \quad (5)$$

These new design formulae were generated by fitting the test results on members with circular openings, thus their application for other perforation shapes requires further interpretation. Nonetheless, the above approaches are not in line with the DSM design philosophy which has been implemented in the design of other resultant actions, i.e. bending, compression (for both perforated and unperforated members) and shear (for unperforated members only). Therefore, a DSM design approach for perforated members in shear is in demand to unify cold-formed steel structural design.

## DSM DESIGN RULES FOR SHEAR FOR UNPERFORATED MEMBERS

The shear strength ($V_n$) including TFA of members without web opening is specified in the AISI S100-12 by

For $\lambda_v \leq 0.776$

$$V_n = V_y \quad (6)$$

For $\lambda_v > 0.776$

$$V_n = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \quad (7)$$

where

$$\lambda_v = \sqrt{\frac{V_y}{V_{cr}}}$$

$V_{cr}$ is elastic shear buckling force of the section,

$$V_{cr} = \frac{k_v \pi^2 E A_w}{12(1-\nu^2)\left(\frac{b}{t}\right)^2} \qquad (8)$$

$k_v$ is shear buckling coefficient for the whole section assuming an average buckling stress in the web which is given in (Pham and Hancock, 2009, 2012b) for plain lipped channels based on the Spline Finite Strip Method (SFSM), b is the depth of the flat portion of the web, t is the thickness of the web, E is Young's modulus, and ν is Poisson's ratio.

$V_y$ is the yield shear load of the flat web, $V_y = 0.6 f_y A_w$ where $A_w$ is the cross sectional area of web element, $f_y$ is the design yield stress. For plate girders, there has been a proposal by Chung et al. (2003) to include the contribution of flanges to the shear strength by adding effective flange areas to the shear area. However, in the cold-formed steel industry, the above expression for $V_y$ has wide acceptance.

## Buckling Capacity

Pham (2015) employed the Spline Finite Strip Method (SFSM) encoded in the Isoparametric Spline Finite Strip Method (ISFSM) program developed by Eccher (2007) to study the buckling capacity of lipped channel section members with central square holes. Three cases (referred to Case A, B and C) distinguished by different methods to apply shear loads were examined. In Case A, uniform shear stress is applied throughout the web panel edges. In Case B and Case C, a shear flow distribution resulting from a shear force parallel with the web is applied at the two end sections as occurs in practice. In order to maintain equilibrium, longitudinal stresses caused by a bending moment (M=V.a, where a is the member length) are applied at one end in an opposite way to balance with the moment caused by the two coupling shear forces (Case B). In Case C, a pair of bending moments with half value (M/2=V.a/2) acting at both end sections in the same direction is applied to balance with the longitudinal shear stresses caused by the two coupling shear forces. The shear buckling coefficients ($k_v$) corresponding to the ratio d/b of the opening size (d) to the flat depth of the web (b) are shown in **Fig. 3**. The difference in $k_v$ between the three cases is relatively small, presumably because shear predominantly governs the buckling behaviour over the bending effects. These values take into account the influence of the cross-section as a whole and the simply supported boundary conditions. They can be used to calculate the $V_{cr}$ for use in the DSM. This paper utilizes the values of $k_v$ based on Case B in which the stress distribution matches the one produced by the experiments.

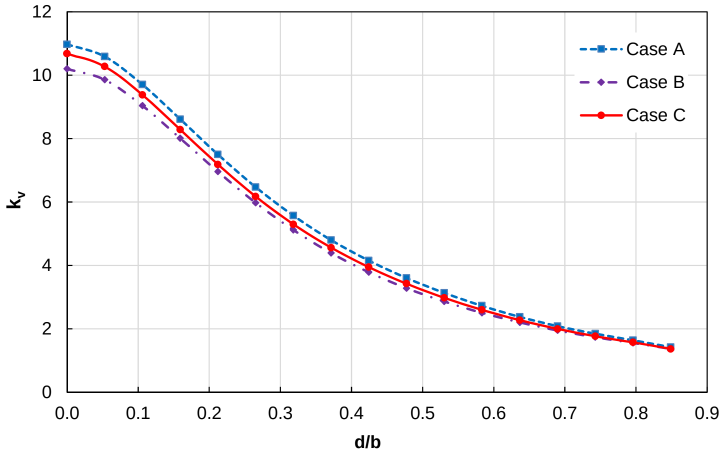
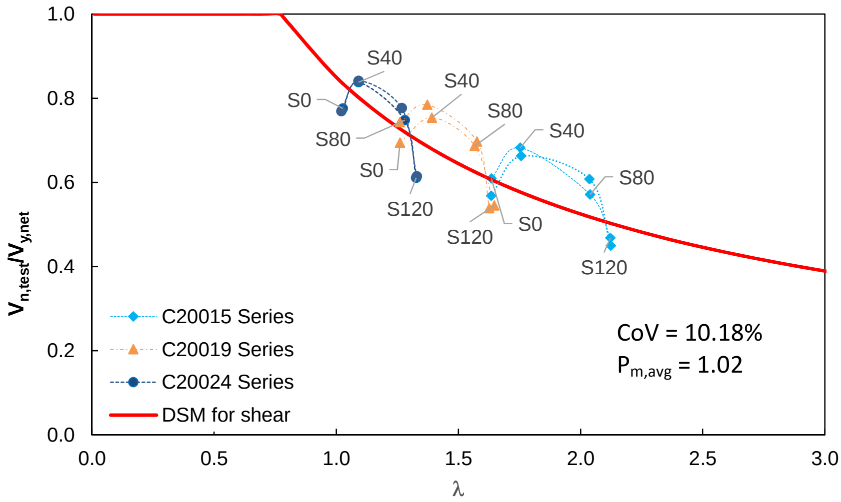



**Fig. 3.** The variation of shear buckling coefficients in three cases

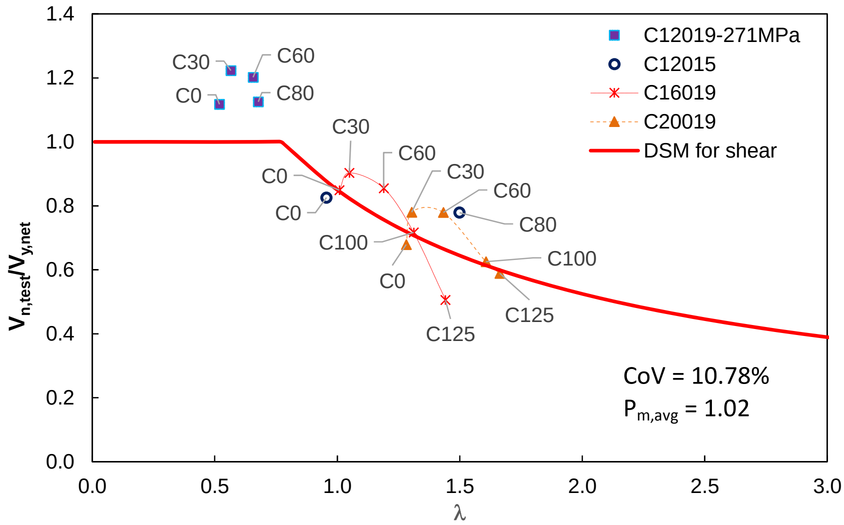
## Shear Strength

There has not been a successful attempt to develop DSM design formulae for perforated cold-formed sections in shear alone although there was a proposal to use either the $V_y$ of the unreduced cross-section or $V_{y,net}$ based on the net section at the opening location (Pham et al., 2016). The test data (Pham et al., 2014, 2016, Keerthan and Mahendran, 2013) are plotted against the DSM design curve for shear with tension field action where the yield shear load is taken as the yield load of the net section ($V_{y,net}$) as shown in **Fig. 4** and **Fig. 5**. The abscissa depicts the section slenderness $\left(\lambda = \sqrt{V_y / V_{cr}} = \sqrt{V_{y,net} / V_{cr}}\right)$ while the odinate represents the ratio of the predominantly shear test results ($V_{n,test}$) to the yield shear load ($V_y = V_{y,net}$). It is noted that in the second test series, the circular opening shape is transformed to the equivalent square by the expression d = 0.825D where d is the square size and D is the circle diameter. This conversion is clarified in the following sections. For both test programs, the data noticeably tends to systematically deviate from the target curve when the openings become substantial. For relatively small perforations, the use of $V_{y,\ net}$ seems to be acceptable but it becomes unconservative when applied for members with large cut-outs. The coefficients of variation corresponding to the above cases are relatively significant, 10.18% and 10.78% respectively. Thus, it is necessary to determine $V_y$ appropriately in order to improve the current design rules.




* S40 denotes square hole with size of 40 mm

**Fig. 4.** Predominantly shear tests at USYD on members with square holes




* C30 denotes circular hole with diameter of 30 mm

**Fig. 5.** Predominantly shear tests at QUT on members with circular holes

## STRATEGY FOR A NEW APPROACH

### Motivation

**Fig. 6** displays the load versus the vertical deformation curves for the tests on the USYD 1.9 mm thick series with square openings. It is noticeable that the test with large hole (C20019-S120) shows ductile behavior characterized by a significant flat plateau at the peak range. This behavior, together with the failure mode as shown in **Fig. 7**, implies that a yielding pattern has been formed and spread out over the cross- sections at the four corners of the opening, allowing substantial plastic deformation to happen before reaching failure mechanism. In the other words, plastic hinges have likely occurred locally at the four opening corners as well recognized in Vierendeel mechanism (Chung et al., 2001). The occurrence and propagation of the cracks at the corners occurred well after the yield plateau and are outside the scope of this paper.

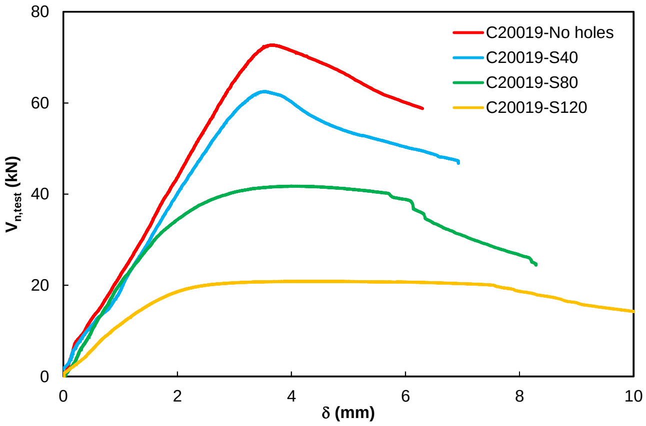



**Fig. 6.** Load – displacement curves for the shear tests on C20019 series

**Fig. 7.** Failure mode on shear test on C20019-S120 member

**Fig. 8** shows the experimental results conducted by Keerthan and Mahendran (2013) on channel members with circular openings. The same sections with two aspect ratios (shear span / web depth) of 1.0 and 1.5 have been tested. It is of interest that for specimens with large openings, there is only a small difference in the shear strength between members with different aspect ratios even though the discrepancy is clearly noticeable for members with smaller holes. The graph indicates two possible facts (i) conventional bending moment has become influential in the shear capacity of slightly perforated members with an aspect ratio of 1.5, (ii) the same failure mechanism as described above might occur for experiments on large web opening with the two different aspect ratios.

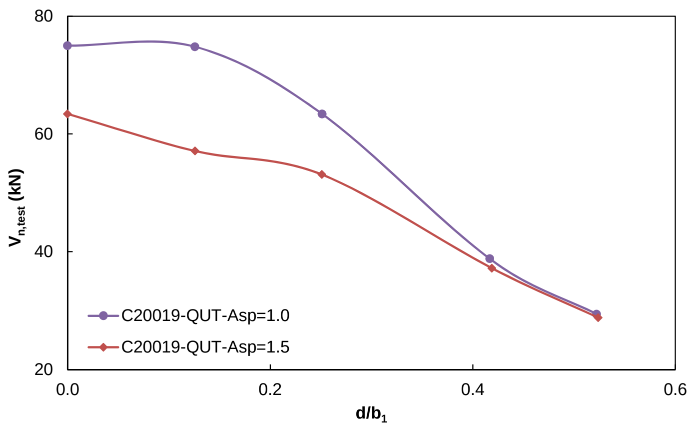



**Fig. 8.** Test results for C20019 members with different aspect ratios and hole sizes

All of the above evidence encourages the implementation of the Vierendeel mechanism into the shear resistance of perforated members in shear.

**Vierendeel Mechanism**

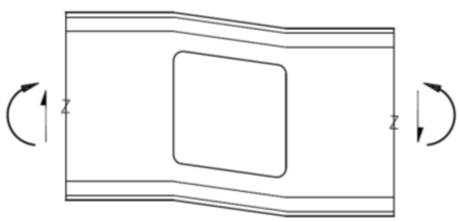



**Fig. 9.** Vierendeel mechanism for C-section perforated member

The Vierendeel truss has been well-known in structural design where the diagonal bars are eliminated, thus enforcing the chords to be stressed in the combination of bending, shear and compression. To transfer those actions, the joints must be rigid compared with the idealized pin connections in conventional trusses. The Vierendeel trusses are widely applicable to bridges and buildings to create large openings for their functionality or aesthetics. In the absence of instability, a failure mechanism is formed in a Vierendeel truss which is characterised by the formation of plastic hinges at corners provided that the structure is ductile enough. A substantially perforated cold-formed member can be viewed as a Vierendeel truss as demonstrated in **Fig. 9** where the shear, in lieu of being resisted by the web element as usual, is transferred through the opening by local bending at the top and bottom segments of the perforated section, i.e. by Vierendeel moment or secondary moment.

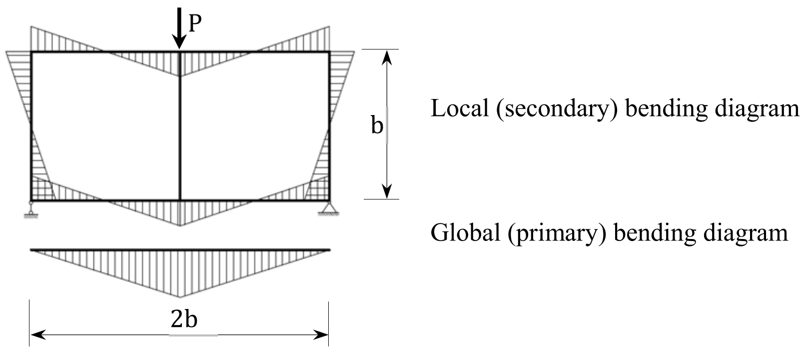



**Fig. 10.** Global bending diagram and local Vierendeel action resultant

**Fig. 10** illustrates the secondary and global (primary) bending moment diagrams in an ideal Vierendeel truss under a centre point load. Each horizontal element is subjected to both local and global actions except at the contra-flexural point at the mid- section.

Once the global actions are negligible, as reasonably applicable for shear tests with the aspect ratio of 1.0, the shear carried out over the opening can be conveniently determined as:

$$V = \frac{4M_{pv}}{d} \tag{9}$$

where:

$M_{pv}$ is the plastic bending capacity of the top (or bottom) segment above (or below) the opening, including the flanges and lips provided that the hole is centrally located. For cold-formed steel sections, the rounded corners are considered as squares for simplicity. d is the width of the web opening.

The reason to adopt the plastic bending moment capacity, not the first yield moment capacity even for thin sections in the above expression is explained and justified in the following sections.

**A model to determine yield shear load for channel sections**

As discussed earlier, the DSM shear design format requires two inputs, the buckling capacity ($V_{cr}$) and the shear load at yielding ($V_y$). The $V_{cr}$ is readily available as detailed above. A practical model is required to determine $V_y$. It is worth noting that the yield shear load $V_y$ is a *theoretical value* obtained from the equation $V_y = 0.6f_yA_w$. The expression implies the assumption that only the flat portion of the web contributes to shear resistance and that the flat web is *fully effective*, i.e. no buckling. It is also likely that the compression flanges of cold-formed sections are restrained properly in practice by attaching to sheathings or flooring boards. Therefore, under those assumptions, critical sections can be fully utilized in bending until they reach their plastic bending capacity. That makes the use of **Eqn. 9** to compute $V_y$ from plastic bending capacity sensible and viable. Generally, the shear strength calculated from **Eqn. 9** is not the ultimate member shear strength except for the case that the member is thick enough. The main reason is, to reach the value of plastic bending, structures must not be exposed to any instability including both local and global, thus the coupled shears resulting from that plastic moment is $V_y$, not $V_n$.

Finite element (FE) models have been developed to appropriately simulate the predominantly shear tests by Pham et al. (2014). All the details of the test configuration and the FE models can be found in that reference. To investigate the variation of $V_y$ corresponding to various opening sizes, the same FE models are utilized but the member thickness is changed to 5mm. The substantially thick member is aimed to eliminate any chance of instability, thus producing the shear strength close to the theoretical yield shear load $V_y$.

In **Fig. 11**, the dotted solid curve (—•—) represents the shear strength ($V_{n,Abq}$) obtained from FEA for members with the ratio of square opening size to the flat web depth ($d/b$) ranges from 0.0 to 1.0. As seen, for members with small cut-outs ($d/b$ up to 0.1), the shear strength reduction is negligible. Thereafter, the value $V_{n,Abq}$ starts reducing gradually following a double curvature path. Based on this graph, it is hypothesized that the shear load at yielding is unchanged for member with small holes ($d/b$ up to 0.1), then it linearly decreases up to the ratio of $d/b$ equal to 0.6. The shear behavior of the members with large openings ($d/b$ is equal or larger than 0.6) is governed by the shear derived from the Vierendeel action, which is determined by **Eqn. 9.**

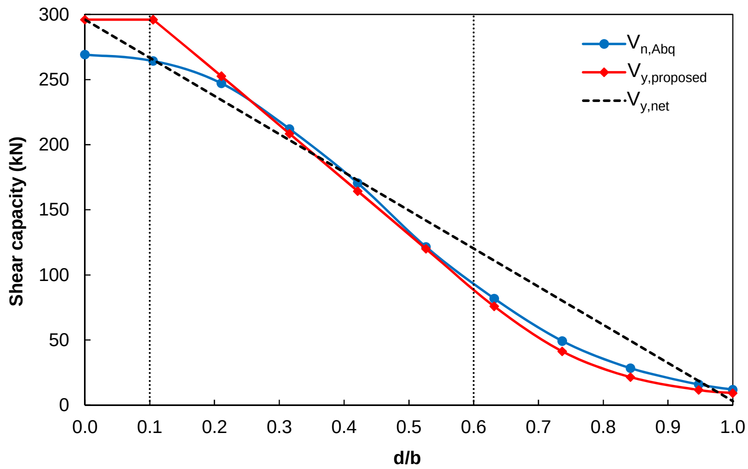



**Fig. 11.** FE results and the model for yield shear load

The new proposed model to determine yield shear load referred as $V_{y,proposed}$ for perforated members is illustrated by the diamond-solid curve (—◆—) in **Fig. 11**. It is worth noting that in case of d/b is equal to 1.0, the shear yielding load vanishes when computed based on the net section ($V_{y,net}$) but it is still captured well by the proposed method due to inclusion of the flanges. The difference between $V_{n,Abq}$ and $V_{y,proposed}$ at d/b = 0.0 is a direct result of the use of $V_y = 0.6f_yA_w$ in the AISI S100-12 which may be slightly unconservative. The new proposal does not require a reduction in the shear capacity until d/b = 0.1 by comparison with the net section approach which requires an immediate reduction.

## A DSM DESIGN FOR SHEAR FOR CHANNEL SECTIONS

### Members with Square Openings

The proposed shear yield load ($V_{y,proposed}$) is employed in the DSM design formulae for shear (**Eqn. 6** and **7**) to verify the predominantly shear tests conducted by Pham et al. (2014 , 2016) on 200 mm deep channel members with three thicknesses of 1.5 mm, 1.9 mm and 2.4 mm. The square opening sizes include 0 mm (unperforated), 40 mm, 80 mm and 120 mm for each thickness. The shear buckling coefficient $k_v$ are extracted from reference (Pham, 2015) depending on the ratio d/b, then the buckling force $V_{cr,SFSM}$ is computed by **Eqn. 8**. The subscript ‘SFSM’ is used to note that the shear buckling load is derived from the coefficient $k_v$ which is obtained by the Spline Finite Strip Method as mentioned earlier.

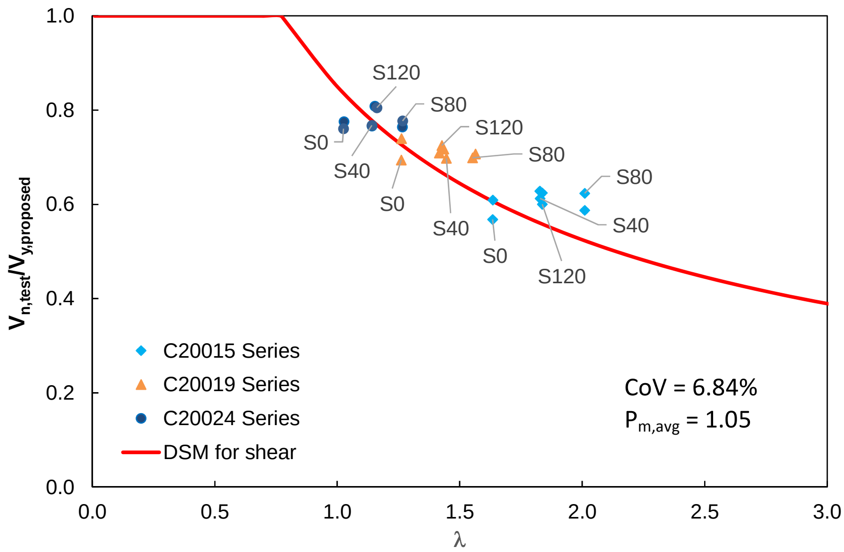



**Fig. 12.** Verifying $V_y$ model with USYD tests

The results are shown in **Fig. 12** where the normalized experimental outcomes $V_{n,test}/V_{y,proposed}$ are plotted against the section slenderness $\left(\lambda = \sqrt{V_{y,proposed}/V_{cr}}\right)$. It is evident that the data follows well the DSM design curve, even when the openings are substantial. The associated coefficient of variation (CoV) and the average $P_{m,avg}$ ratio of $V_{n,test}$ to $V_{n,DSM}$ are 6.84% and 1.05 respectively. This CoV can be compared with that in **Fig. 4** of 10.18%.

**Members with Circular Openings**

The model for yield shear load is also verified against the predominantly shear tests performed by Keerthan and Mahendran (2013) on channel members with the aspect ratio of 1.0. Different section sizes and circular hole diameters were included in their tests.

**Fig. 13** shows a FE simulation of 5 mm thick channel section members in a predominantly shear test with substantial circular opening (d/b = 0.6). The failure mechanism happens as analogous as occurred in the test on square hole (see **Fig. 7**). It includes the formation of four plastic hinges, resulting in large, visible deflection that constitutes the mechanism. This allows the methodology to determine $V_y$ to be applicable for members with circular holes by transforming the circles to the squares by the relation d = 0.825D where d is the square size, D is the circle diameter. Using this transformation, the experimental results are plotted against the DSM curve for shear as shown in **Fig. 14**. A low strength test series ($f_y$ = 271 MPa) and other tests are well captured by the design curve. The corresponding CoV and $P_{m,avg}$ are 5.65% and 1.06 respectively. This CoV can be compared with that using $V_{y,net}$ of 10.78% in **Fig. 5**. Obviously, it is evident that the proposed model to compute $V_y$ for perforated sections are viable for members with aspect ratio of 1.0 and for both circular as well as square openings.

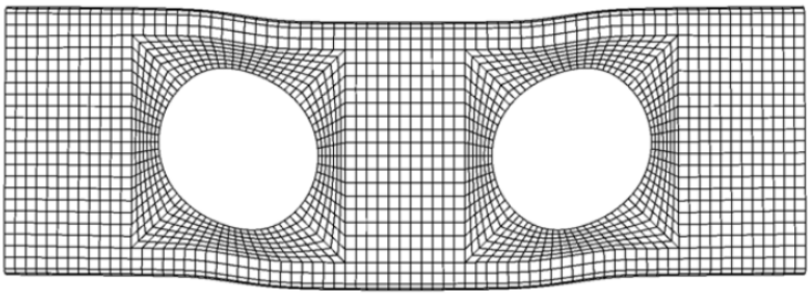


**Fig. 13.** FE simulation of shear tests with circular holes

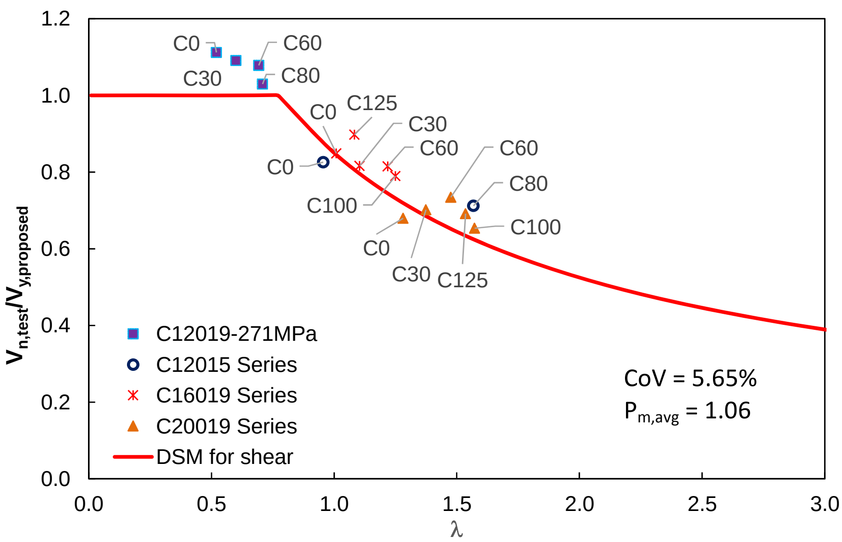



**Fig. 14.** Verifying $V_y$ model with QUT tests

## CONCLUSION

A practical model to compute the yield shear load of sections with square and circular holes has been formulated to describe the transition of failure modes from traditional web shear to Vierendeel mechanism. That gradual transition was supported by the FE simulations of in-plane perforated plates and thick C-section members in shear. The proposed $V_y$ model is introduced into the current DSM design rules for shear to predict well the shear strength of various predominantly shear tests with aspect ratio of 1.0 and with circular as well as square openings.

## ACKNOWLEDGEMENT

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