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Simplification of the Direct Strength Method of Design for Cold-Formed Channels with Holes in Shear

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Abstract

A Direct Strength Method (DSM) of design for cold-formed steel channels with holes in shear has been developed previously using a Vierendeel model. In particular, the model is applied to square, circular, rectangular and slotted holes. Although the model is accurate with cold-formed channels consisting of considerable hole sizes, the model is quite complex to implement into a design Standard such as AS/NZS 4600 or Specification such as AISI S100. In order to simplify the methodology, a cubic fit to the Vierendeel model prediction of the yield shear strength $\left(V_{yh}\right)$ of the section with holes has been made. The fit equation is simply a function of the shear yield load $\left(V_{y}\right)$, the hole depth divided by web depth $\left(d_h/h\right)$ and the hole depth divided by the hole length $\left(d_h/L_h\right)$. The paper gives the development of the equations and a comparison of the method against a large range of test data in the literature.

Keywords: Cold-formed steel; Shear; Direct Strength Method; Simplification; Holes.

1. Introduction

In recent years, cold-formed steel structures have been widely used in the construction field due to the easy fabrication and high strength to weight ratio. In practice, cold-formed steel members are manufactured in order to adapt to the service requirements of the buildings (e.g., plumbing, electrical and heating systems, etc.). In general, the use of holes in cold-formed steel members is the easiest way to overcome building service problems. Consequently, the presence of holes in cold-formed steel members is a fundamental issue that affects the strength of the structures because of changes in the stress distributions at the holes.

In the literature, the effects of web holes on the shear strength of channels without transverse stiffeners were researched by Shan et al. [1], Schuster et al. [2] and Eiler et al. [3]. In their studies, the influence of both rectangular and slotted web openings on the shear strength reduction of channel sections was investigated experimentally. Their test results played a crucial role as a database for calibrating standards and specifications.

More recently, Keerthan & Mahendran [4] carried out a series of tests of lipped channel beams (LCBs) in shear with different sizes of circular web openings. They demonstrated the Shan et al. [1] design equations are too conservative for the shear capacity of LCBs with web openings. As a result, improved design rules were proposed by modifying the shear capacity reduction factors based on the experimental results.

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Recently, Pham and Hancock [5] proposed DSM shear design rules for cold-formed steel channels with central square holes. In their research, a new and simplified model was proposed based on the net web areas for determining the shear yield load $\left(V_{y,net}\right)$. However, the simplified model only applied for channels with small central square holes (i.e. $d_h/h = 0.6$).

To analyze channels with relatively large central square holes (i.e. $d_h/h > 0.6$), a proper and more accurate model of yield loads $\left(V_{vrd}\right)$ based on a Vierendeel mechanism was proposed by S. H. Pham et al. [6]. In their study, a DSM based on the Vierendeel Model was utilized to analyze the shear strength of the perforated channels with circular and square web openings. The model was validated by comparison with the experimental results and Finite Element Method (FEM) results.

Recently, D. K. Pham et al. [7] further modified the Vierendeel Model to account for the influence of rectangular and slotted web openings on the shear behaviour and shear strength of cold-formed channel sections. They used a predominantly shear test procedure utilizing a dual actuator test rig. Thirty-six sections with three aspect ratios $\left(L_h/d_h\right)$ of holes including 1.0, 2.0 and 3.0 were tested. Furthermore, D. K. Pham et al. [8] carried out a parametric study based on the validated FEM in order to study investigate channel sections with relatively large elongated web openings.

It should be noted that the DSM of design based on the Vierendeel Model is capable of handling more complex and general scenarios such as square, circular, rectangular and slotted holes in channel sections with relatively large web openings in comparison with previous models [4-5]. Nevertheless, the model is quite complex [6-7] to implement into a design Standard such as AS/NZS 4600 [9] or Specification such as AISI S100–16 [10]. In order to simplify the methodology, a cubic fit to the Vierendeel model prediction of the yield shear strength $\left(V_{yh}\right)$ of the section with holes is made in this paper.

2. Direct Strength Method for cold-formed sections with and without holes in shear

2.1 Direct Strength Method of design rules in shear of webs

2.1.1 The shear strength of members without transverse web stiffeners without holes

The nominal shear strength $\left(V_n\right)$ of perforated channels without transverse web stiffeners is specified in Section G2.1 in AISI S100–16 [9], and is given by

$$\text{for } \lambda_v \le 0.815 : V_n = V_y \quad (1)$$

$$\text{for } 0.815 < \lambda_v \le 1.227 : V_n = 0.815\sqrt{V_{cr}V_y} \quad (2)$$

$$\text{for } \lambda_v > 1.227 : V_n = V_{cr} \quad (3)$$

where $\lambda_v = \sqrt{V_y/V_{cr}}$; $V_y = 0.6A_wF_y$ is the yield shear force of cross-section; $V_{cr} = \left(k_v\pi^2EA_w\right)\Big/\left[12\left(1-\mu^2\right)\left(h/t\right)^2\right]$ is the elastic shear buckling force; $A_w = ht$ is area of web element; h is depth of flat portion of web measured along plane of web; t is web thickness; F_y is design yield stress; k_v is shear buckling coefficient; E denotes modulus of elasticity of steel; μ is Poisson's ratio.

2.1.2 The shear strength of members with transverse web stiffeners without holes

The nominal shear strength $\left(V_n\right)$ of perforated channels with transverse web stiffeners is specified in Section G2.2 in AISI S100–16 [9], and is calculated as follows

$$\text{for } \lambda_v \le 0.776 : V_n = V_y \quad (4)$$

$$\text{for } \lambda_v > 0.776 : V_n = \left[1-0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \quad (5)$$

2.1.3 New proposal for the shear strength of members without transverse web stiffeners

A new proposal currently under ballot with the AISI specification committee allows for the post-buckling strength of members without transverse stiffeners at high web slenderness, and is given by

$$\text{for } \lambda_v \le 0.587 : V_n = V_y \tag{6}$$

$$\text{for } \lambda_v > 0.587 :$$
$$V_n = \left[1 - 0.25\left(\frac{V_{cr}}{V_y}\right)^{0.65}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.65} V_y \tag{7}$$

2.2 Proposals for Direct Strength Method of design for shear with square and circular holes

2.2.1 Proposal based on net web area model

The DSM shear design rules for cold-formed steel channels with central square holes was proposed by Pham and Hancock [5] where the proposed shear yield load based on net web area referred as $\left(V_{y,\text{net}}\right)$ is utilized to replace the conventional shear yield load $\left(V_y\right)$, and is given by

$$V_{y,net} = 0.6\left(h - d_h\right)F_y t \tag{8}$$

where d_h is the depth of the hole.

2.2.2 Proposal based on the Vierendeel model

A proper and more accurate model of yield loads $\left(V_{vrd}\right)$ was proposed by S. H. Pham et al. [6] where the proposed shear yield load $\left(V_{yh}\right)$ based on a Vierendeel mechanism is used to replace the conventional shear yield load $\left(V_y\right)$ in Equations (4)-(7) as follows

$$\text{when } 0 < \frac{d_h}{h} \le 0.1 : V_{yh} = V_y \tag{9}$$

$$\text{when } 0.1 < \frac{d_h}{h} < 0.6 :$$
$$V_{yh} = V_y - 2\left(\frac{d_h}{h} - 0.1\right)\left(V_y - V_{vrd,0.6}\right) \tag{10}$$

$$\text{when } \frac{d_h}{h} \ge 0.6 : V_{yh} = V_{vrd} \tag{11}$$

where V_{vrd} is determined by Equation (12); $V_{vrd,0.6}$ is the value of V_{vrd} that is computed for the perforated section with the ratio $d_h/h = 0.6$.

$$V_{vrd} = \frac{4M_{pv}}{L_h} \tag{12}$$

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, as shown in Figure 1, L_h is the width of the web opening.

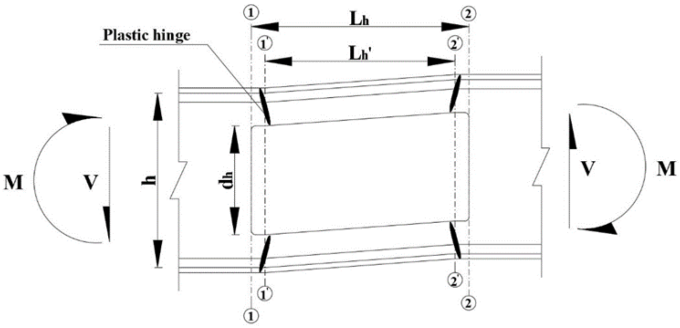

Figure 1: Vierendeel mechanism and location of plastic hinges for C-channels in shear with elongated holes (D.K. Pham et al. [7]).

2.3 Proposals for Direct Strength Method of design for shear with square, circular, rectangular and slotted holes based on Vierendeel model

D. K. Pham et al. [7] further modified the Vierendeel Model to investigate the influences of elongated web openings on the shear behaviour and shear strength of cold-formed channel sections as given by

$$\text{when } 0 < \frac{d_h}{h} \le 0.1 : V_{yh} = V_y \tag{13}$$

$$\text{when } 0.1 < \frac{d_h}{h} < m :$$
$$V_{yh} = V_y - \left(\frac{1}{m - 0.1}\right)\left(\frac{d_h}{h} - 0.1\right)\left(V_y - V_{vrd,m}.v_i\right) \tag{14}$$

$$\text{when } \frac{d_h}{h} \ge m : V_{yh} = V_{vrd}.v_i \tag{15}$$

in which $m = 0.715 - 0.125\left(L_h/d_h\right) + 0.01\left(L_h/d_h\right)^2$; L_h is the length of the hole; $v_i = 0.745 + 0.28\left(L_h/d_h\right) - 0.025\left(L_h/d_h\right)^2$; $V_{vrd,m}$ is the value of V_{vrd} computed for the perforated sections when $d_h/h = m$.

It can be seen from Equations (9)-(15) that the model of the yield loads $\left(V_{yh}\right)$ based on the Vierendeel model is quite complex to calculate. Therefore, based on the previous database, a cubic fit to the Vierendeel model prediction of the yield shear strength $\left(V_{yh}\right)$ of the section with holes is made in this paper to simplify the calculation procedure.

3. Simplification of the Direct Strength Method of design for cold-formed sections with holes in shear

3.1 The shear strength of members without transverse web stiffeners

The nominal shear strength $\left(V_n\right)$ of perforated channels without transverse web stiffeners is proposed as follows

$$\text{for } \lambda_v \le 0.587 : V_n = V_{yh,prop} \tag{16}$$

$$\text{for } \lambda_v > 0.587 :$$
$$V_n = \left[1 - 0.25\left(\frac{V_{cr,prop}}{V_{yh,prop}}\right)^{0.65}\right]\left(\frac{V_{cr,prop}}{V_{yh,prop}}\right)^{0.65} V_{yh,prop} \tag{17}$$

in which $V_{cr,prop} = \left(\alpha k_v \pi^2 E A_w\right) \big/ \left[12\left(1-\mu^2\right)\left(h/t\right)^2\right]$ is the proposed elastic shear buckling force; $\alpha = \left[1 - 0.4\left(L_h^{eq} - d_h^{eq}\right)/h\right]^2$; d_h^{eq} and L_h^{eq} are respectively the equivalent depth and length of the web opening determined by Equations (19)-(20); $V_{yh,prop}$ is the proposed yield shear load of the flat web determined by Equations (21)-(22); k_v is the shear buckling coefficient proposed by S. H. Pham et al. [6]

$$\begin{aligned} k_v &= 6.15\frac{h}{a} - 3.63\frac{d_h^{eq}}{h} - 19.58\frac{d_h^{eq}}{a} + \ldots \\ &\ldots + 13.88\frac{\left(d_h^{eq}\right)^2}{ha} + 0.57\frac{b_f}{h} + 4.86 \end{aligned} \tag{18}$$

where a is the length of the shear span; b_f is the overall width of the flange.

The equivalent depth and length of the web opening follow the transformed formulas, as developed by D. K. Pham et al. [7]

$$d_h^{eq} = d_h\left(0.003\frac{L_h}{d_h} + 0.822\right) \tag{19}$$

$$L_h^{eq} = \frac{0.865 L_h d_h}{d_h^{eq}} \tag{20}$$

The proposed yield shear load ($V_{yh,prop}$) of the flat web is determined based on the following cubic equations

$$\text{when } 0 < \frac{d_h^{eq}}{h} \le 0.1 : V_{yh,prop} = V_y = 0.6 F_y h t \tag{21}$$

$$\begin{aligned} &\text{when } \frac{d_h^{eq}}{h} > 0.1 : V_{yh,prop} = V_y + a_0 V_y\left(\frac{d_h^{eq}}{h} - 0.1\right) \\ &+ a_1 V_y\left(\frac{d_h^{eq}}{h} - 0.1\right)^2 + a_2 V_y\left(\frac{d_h^{eq}}{h} - 0.1\right)^3 \end{aligned} \tag{22}$$

in which $a_0 = -0.173 - 0.9252\left(L_h^{eq}/d_h^{eq}\right) + 0.0524\left(L_h^{eq}/d_h^{eq}\right)^2$;
$a_1 = -3.4095 + 1.9922\left(L_h^{eq}/d_h^{eq}\right) - 0.0995\left(L_h^{eq}/d_h^{eq}\right)^2$;
$a_2 = 2.684 - 1.084\left(L_h^{eq}/d_h^{eq}\right) + 0.0466\left(L_h^{eq}/d_h^{eq}\right)^2$.

3.2 The shear strength of members with transverse web stiffeners

The proposed nominal shear strength $\left(V_n\right)$ of perforated channels with transverse web stiffeners is given by

$$\text{for } \lambda_v \le 0.776 : V_n = V_{yh,prop} \tag{23}$$

$$\text{for } \lambda_v > 0.776 :$$
$$V_n = \left[1 - 0.15\left(\frac{V_{cr,prop}}{V_{yh,prop}}\right)^{0.4}\right]\left(\frac{V_{cr,prop}}{V_{yh,prop}}\right)^{0.4} V_{yh,prop} \tag{24}$$

where $V_{cr,prop}$ and $V_{y,prop}$ are given in 3.1 above.

4. Comparison of the Simplified Direct Strength Method of design for shear with the previous methods

4.1 Comparison of the yield shear load $\left(V_y\right)$ based on net web area model and Vierendeel model

4.1.1 Aspect ratio $\left(AR_h = L_h^{eq}/d_h^{eq} = 1.0\right)$

The validation of the Simplified DSM of design based on the cubic fit to the Vierendeel model prediction of the yield shear strength $\left(V_{yh}\right)$ is illustrated in Figures (2)-(25). In particular, the cubic curve is compared with the reference solution generated from the Vierendeel model. It can be seen that the two curves are almost indistinguishable. In addition, it is worth pointing out that the new curve demonstrates more accurate results in comparison with the net web area model.

The cubic curve decreases consistently with the Vierendeel model proposed by D. K. Pham et al. [7] throughout the range of d_h^{eq} / h (i.e., $0 \leq d_h^{eq} / h \leq 1$) and finally converges to the Vierendeel curve where the web openings are relatively large (i.e., $d_h^{eq} / h > 0.6$). On the contrary, the net web area model proposed by Pham and Hancock [5] overestimates the yield shear load $\left(V_{yh}\right)$ with large web openings (i.e., $d_h^{eq} / h > 0.6$).

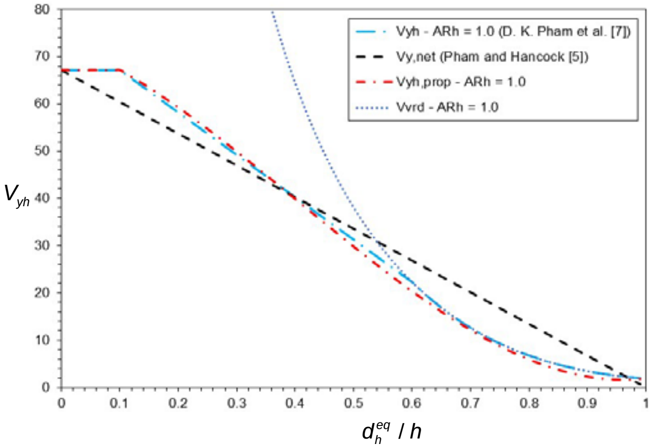

Figure 2: The yield shear load of the flat web based on different models in channel section - C20010*

* C-lipped channel section with a depth of 200 mm and a thickness of 1.0 mm

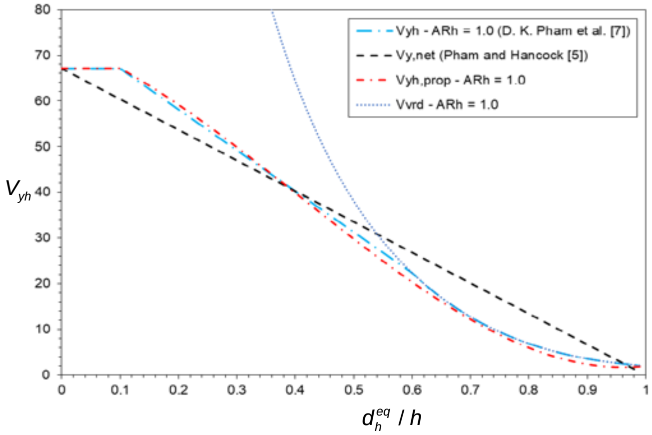

Figure 3: The yield shear load of the flat web based on different models in channel section - C20015

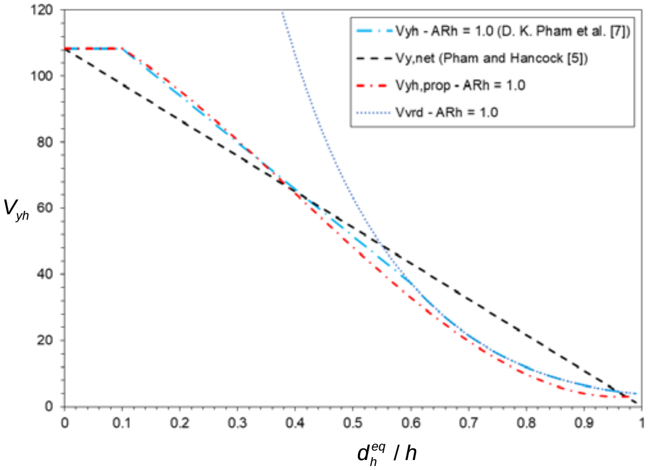

Figure 4: The yield shear load of the flat web based on different models in channel section - C20019

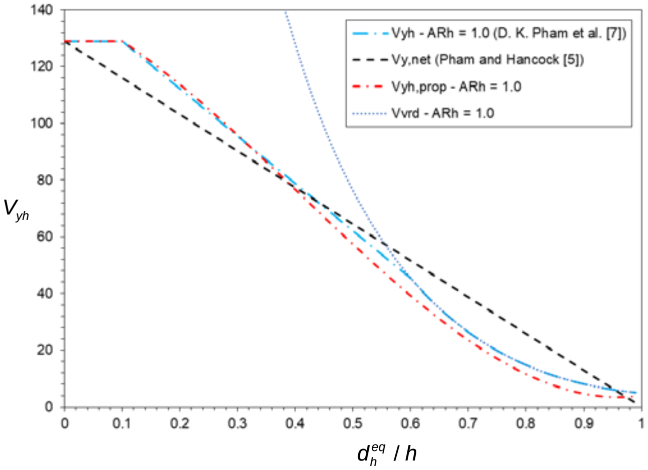

Figure 5: The yield shear load of the flat web based on different models in channel section - C20024

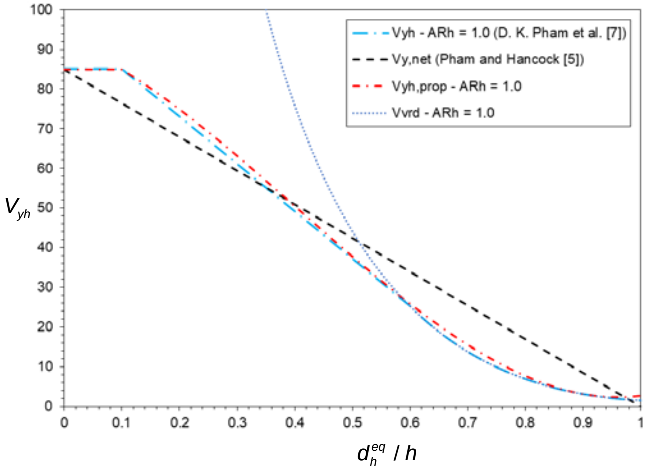

Figure 6: The yield shear load of the flat web based on different models in channel section - C25010

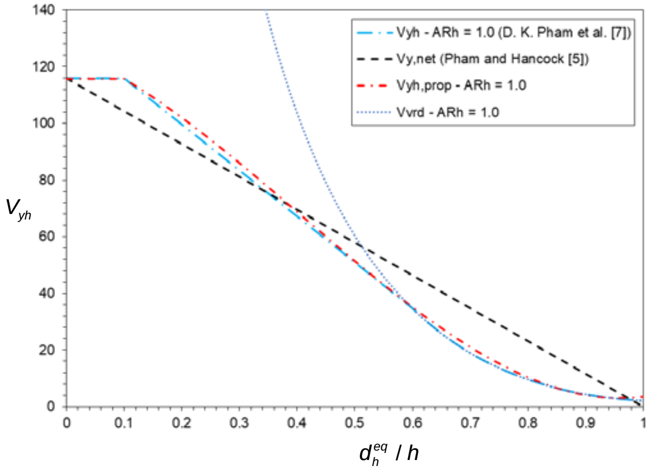

Figure 7: The yield shear load of the flat web based on different models in channel section - C25015

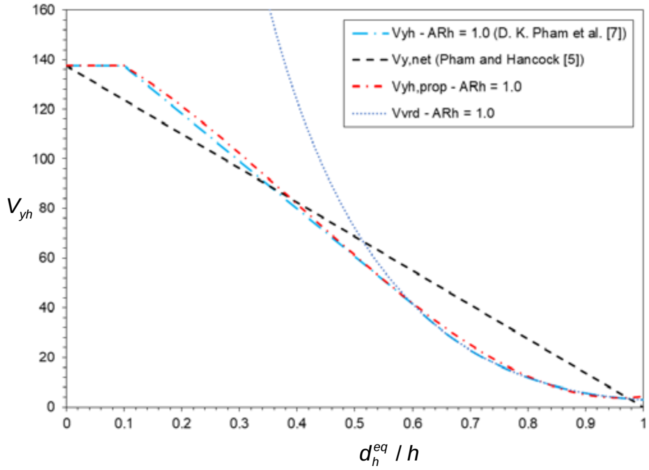

Figure 8: The yield shear load of the flat web based on different models in channel section - C25019

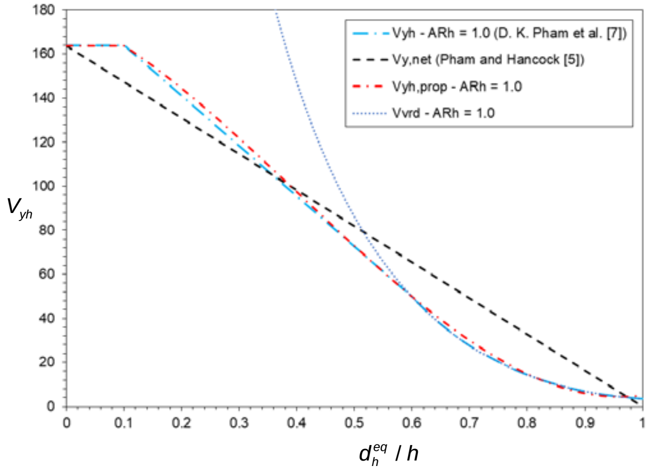

Figure 9: The yield shear load of the flat web based on different models in channel section - C25024

4.1.2 Aspect ratio $\left(AR_h = L_h^{eq} / d_h^{eq} = 2.0\right)$

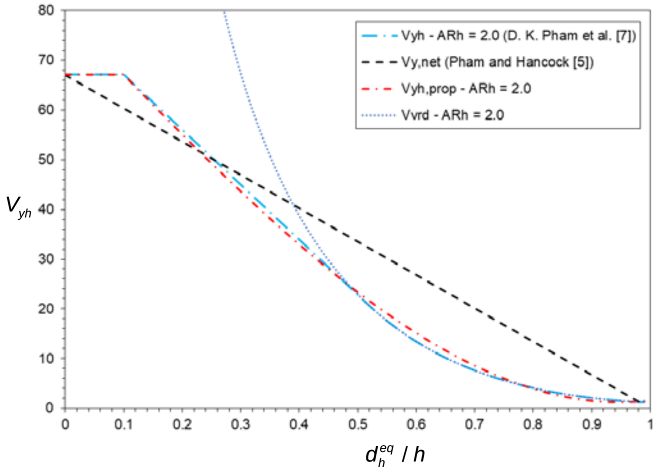

Figure 10: The yield shear load of the flat web based on different models in channel section - C20010

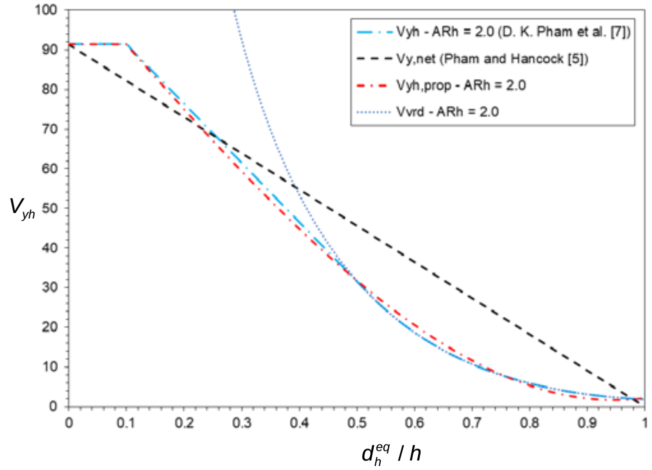

Figure 11: The yield shear load of the flat web based on different models in channel section - C20015

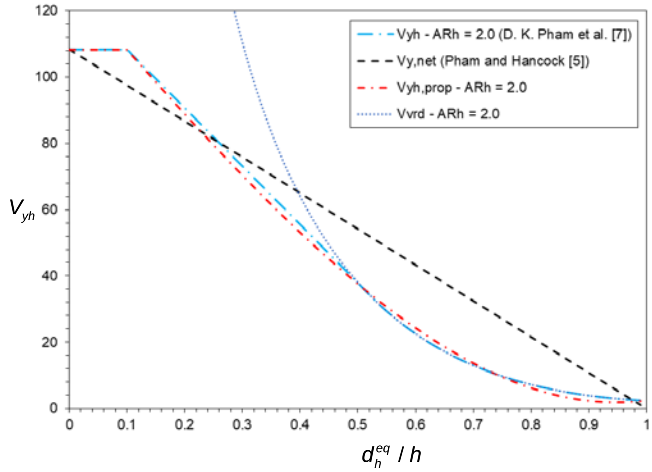

Figure 12: The yield shear load of the flat web based on different models in channel section - C20019

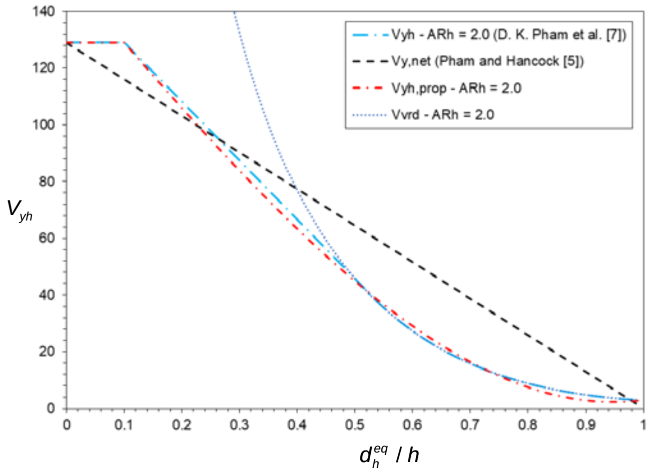

Figure 13: The yield shear load of the flat web based on different models in channel section - C20024

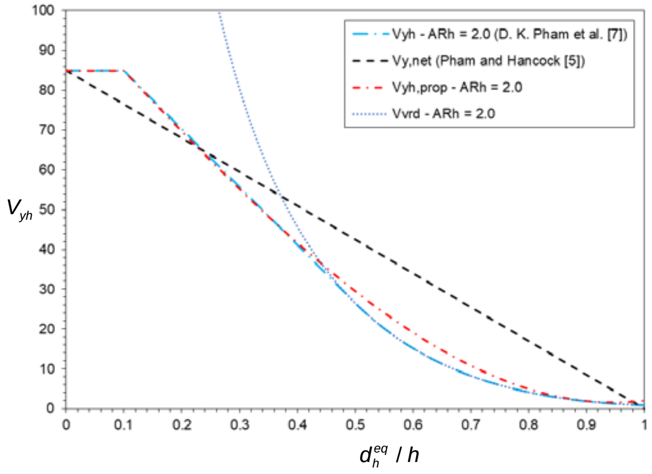

Figure 14: The yield shear load of the flat web based on different models in channel section - C25010

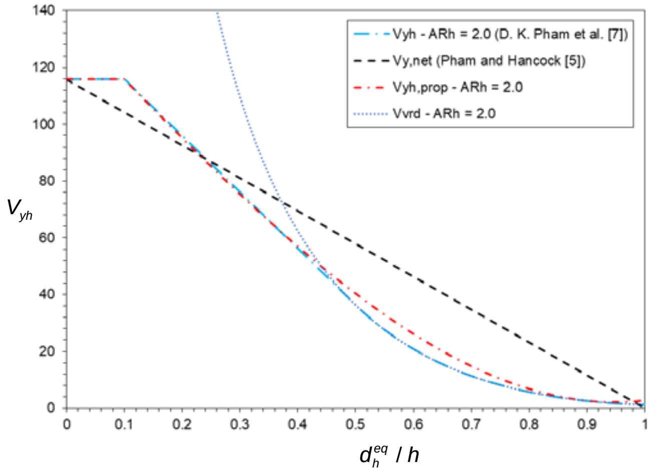

Figure 15: The yield shear load of the flat web based on different models in channel section - C25015

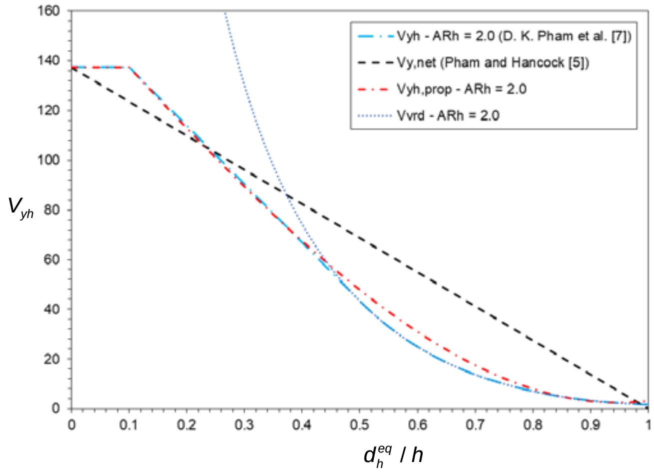

Figure 16: The yield shear load of the flat web based on different models in channel section - C25019

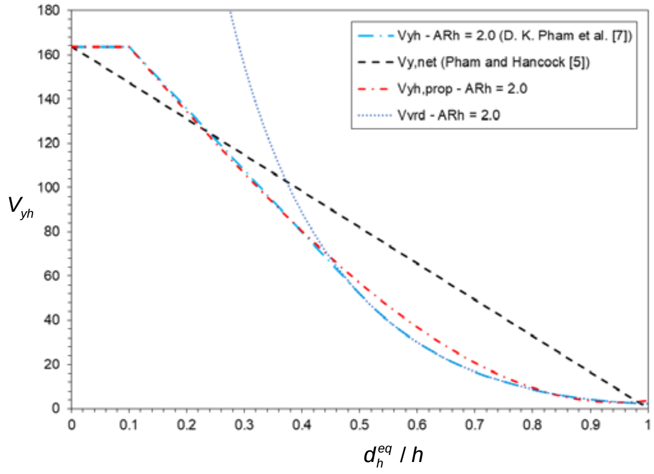

Figure 17: The yield shear load of the flat web based on different models in channel section - C25024

4.1.3 Aspect ratio $\left(AR_h = L_h^{eq} / d_h^{eq} = 3.0\right)$

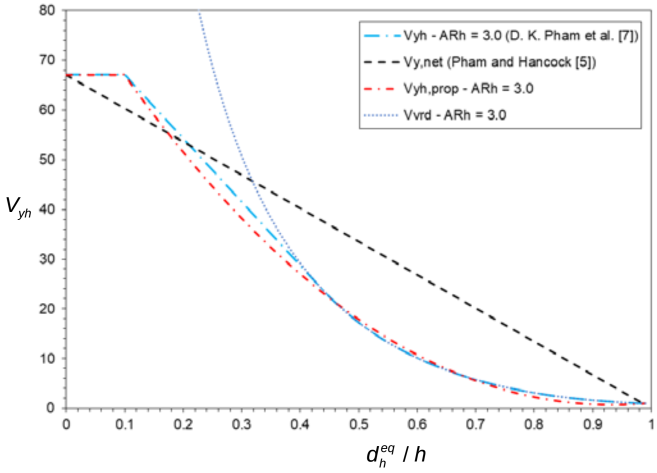

Figure 18: The yield shear load of the flat web based on different models in channel section - C20010

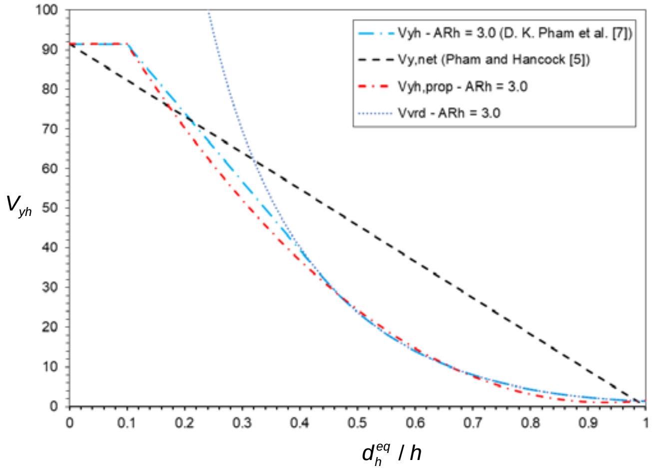

Figure 19: The yield shear load of the flat web based on different models in channel section - C20015

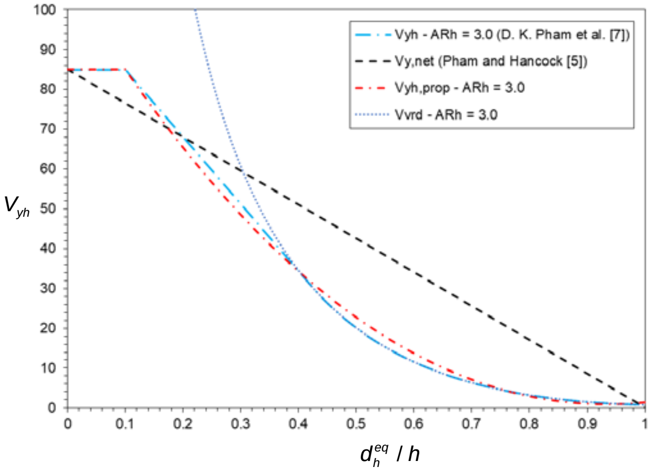

Figure 22: The yield shear load of the flat web based on different models in channel section - C25010

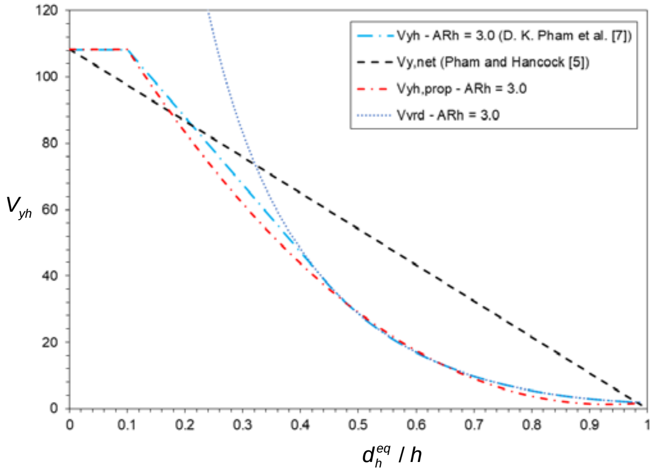

Figure 20: The yield shear load of the flat web based on different models in channel section - C20019

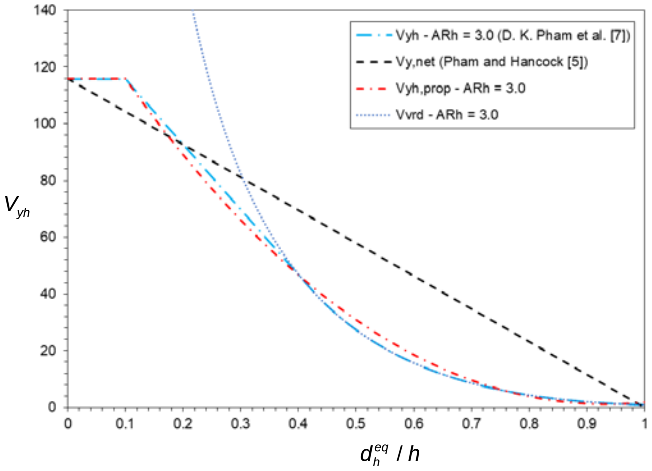

Figure 23: The yield shear load of the flat web based on different models in channel section - C25015

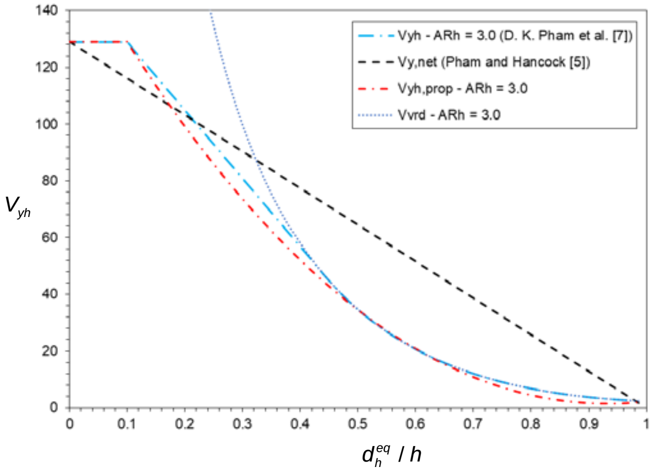

Figure 21: The yield shear load of the flat web based on different models in channel section - C20024

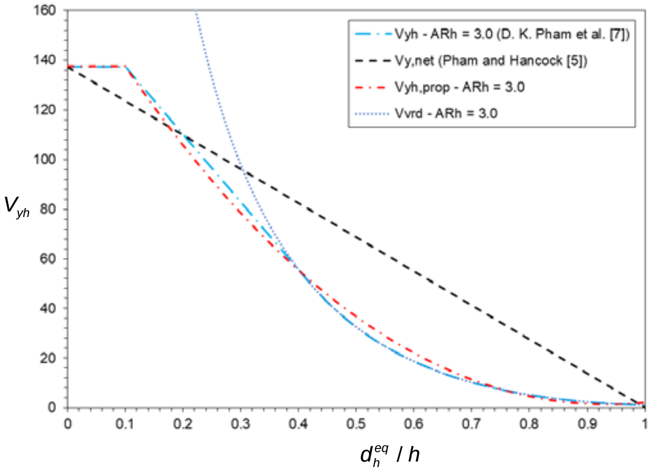

Figure 24: The yield shear load of the flat web based on different models in channel section - C25019

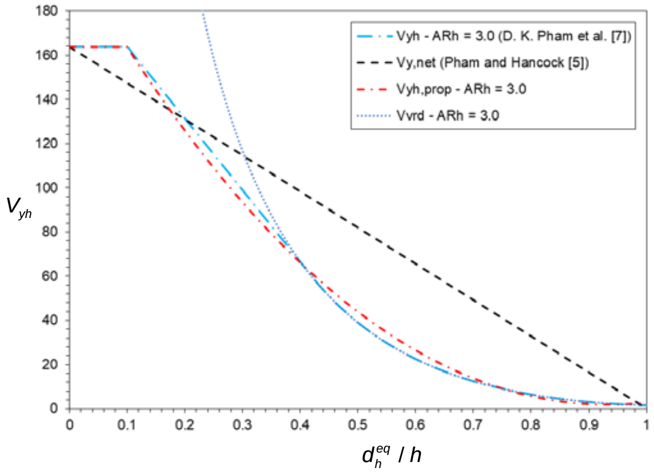

Figure 25: The yield shear load of the flat web based on different models in channel section - C25024

4.2 *Comparison of the Simplified Direct Strength Method of design in shear with the previous test results*

The validity of the Simplified DSM of design based on the cubic fit is also confirmed by good agreement in comparison with the previous test results indicated in Figures (26)-(27). Clearly, the Simplified DSM exhibits an accurate curve to determine the nominal shear strength (V_n) of perforated channels for cases with and without transverse web stiffeners. It is to be noted that the Simplified DSM shear curve overestimates the shear strength (V_n) of perforated channels in comparison with the test results from Shan et al. [1] whereas the whole test database from Schuster et al. [2], Eiler et al. [3], Keerthan & Mahendran [4], Pham and Hancock [5], S. H. Pham et al. [6] and D. K. Pham et al. [7] again verifies the accuracy of the current Simplified DSM of design.

It is apparent that the calculation of the DSM design loads for shear is simplified by means of the cubic fit to the Vierendeel model prediction while the current Simplified DSM of design loads illustrates the efficiency and the accuracy in comparison with the previous complex model.

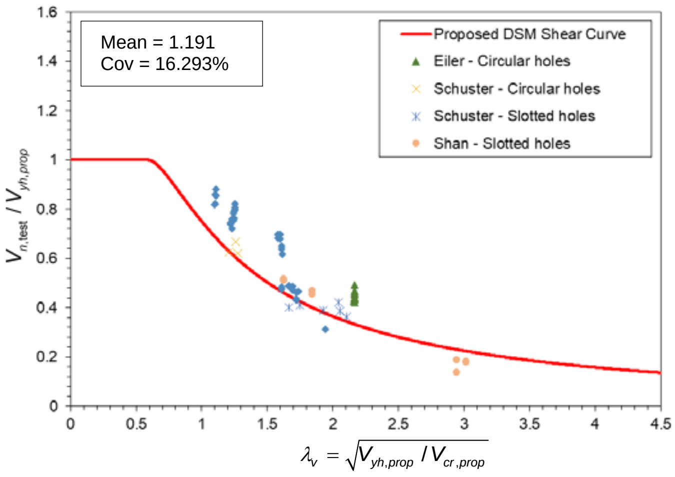

Figure 26: Shear test results based on $V_{yh,prop}$ versus DSM shear curves – without transverse web stiffeners

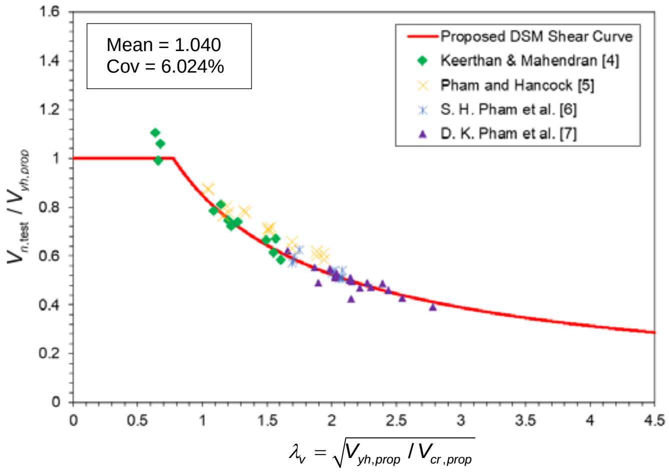

Figure 27: Shear test results based on $V_{yh,prop}$ versus DSM shear curves – with transverse web stiffeners

5. Conclusions

An efficient and accurate Simplified DSM of design has been successfully implemented for determining the shear strength (V_n) of perforated channels with square, circular, rectangular and slotted holes. By the means of a cubic fit to the Vierendeel model prediction, the DSM of design for shear is simplified in comparison with the previous complex model. The results from the simplified model exhibits excellent agreement with the full test database.

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References

[1] M.Y. Shan, R.A. LaBoube, W.w. Yu, Behavior of web elements with openings subjected to bending, shear and the combination of bending and shear, University of Missouri-Rolla. Rolla, Missouri, 1994.

[2] R. Schuster, C. Rogers, A. Celli, Research into cold formed steel perforated c-sections in shear, Program Rep. No. 1 Phase I CSSBI/IRAP Project, 1995.

[3] M.R. Eiler, R.A. LaBoube, W.W. Yu, Behaviour of web elements with openings subjected to linearly varying shear, University of Missouri-Rolla, 1997.

[4] P. Keerthan, M. Mahendran, Experimental studies of the shear behaviour and strength of lipped channel beams with web openings, Thin-Walled Structures. (73) (2013) 131–144.

[5] C.H. Pham and G.J. Hancock, Shear tests and design of cold-formed steel channels with central square holes, Thin-walled Structures. (149) (2020) 106650.

[6] S.H. Pham, C.H. Pham, C.A. Rogers and G.J. Hancock, Shear strength experiments and design of cold-formed steel channels with web holes, Journal of Structural Engineering, ASCE. (164) (2020) 04019173.

[7] D.K. Pham, C.H. Pham, S.H. Pham and G.J. Hancock, Experimental investigation of high strength cold-formed channel sections in shear with rectangular and slotted web openings, Journal of Constructional Steel Research. (165) (2020) 105889.

[8] D.K. Pham, C.H. Pham and G.J. Hancock, Parametric study for shear design of cold-formed channels with elongated web openings, Journal of Constructional Steel Research. (172) (2020) 106222.

[9] AS/NZS 4600:2018, AS 4600 cold-formed steel structures, AS/NZS 4600:2018, Standards Australia, 2018, (Standards Australia/Standards New Zealand).

[10] AISI S100–16, North American specification for the design of cold-formed steel structural members, AISI S100–16, AISI, Washington, DC, U.S.A, 2016.