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Shear Buckling Behaviour of Cold-Formed Steel Members With Web Openings

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Abstract. Cold-formed steel (CFS) sections have become a common choice in modern construction because they offer considerable strength while remaining lightweight and straightforward to install. When openings are cut into the web to accommodate building services, however, the way these members carry shear can change substantially. In this work, the behaviour of channel sections containing such openings is examined in detail. A series of nonlinear Finite-Element (FE) simulations was created, each including the influence of initial geometric imperfections, and the numerical responses were compared with available test data to ensure they reflected physical behaviour. After validation, the models were used to study how different variables, including the shape of the opening, its size, and the slenderness of the web, affect shear resistance. The numerical results indicate a sharp drop in capacity when the openings become large or when the web is relatively thin, with the most severe cases showing reductions approaching 90% for opening size and roughly one-third for web slenderness.

Keywords: Cold-Formed Steel; Shear Buckling; Web Opening; FE Modelling; Channel Section

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* хат-хабар үшін автор

Introduction

Cold-formed steel (CFS) has become an integral material in modern construction, used not only in secondary framing but increasingly as a primary structural component. It appears in systems such as sheathed wall panels [1–3] and various forms of moment-resisting assemblies [4–10]. Its growing use is driven by several practical advantages: a favourable strength-to-weight ratio, relatively low fabrication and handling cost, and the ability to transport and assemble components with minimal effort. Unlike hot-rolled steel, CFS sections are shaped without the application of heat, allowing thin steel sheets to be formed into a wide range of profiles and giving designers considerable geometric flexibility [11–16].

As higher-strength steels have become more readily available and construction methods have evolved, the overall demand for CFS has steadily increased, particularly in low- to mid-rise structures. Commonly adopted profiles include channels, Z-sections, and hat-shaped members. In routine building practice, openings are frequently cut into the webs of these members to accommodate electrical conduits, plumbing runs, and HVAC services. Although necessary, these penetrations disturb the original stress field and can reduce both the shear resistance and the stability of the member, influencing the form and progression of buckling [17]. The Direct Strength Method (DSM), introduced by Schafer [18], provides an alternative to the classical Effective Width Method [19] for predicting the strength of CFS elements. DSM relies on elastic buckling analyses, often undertaken using tools such as CUFSM [20], to estimate capacity and is incorporated into the AISI S100-16 design standard [21]. Early work on the influence of web openings on shear behaviour was conducted by Shan et al. [22], who identified the need for reduction factors due to shortcomings in existing AISI provisions.

Subsequent work by Eiler et al. [23] extended these ideas to cases involving non-uniform shear, producing revised coefficients that were later adopted into the S100-16 specification. Keerthan and Mahendran [24] carried out experimental testing on lipped channel beams with circular openings and complemented their work with ABAQUS-based finite-element studies [25], concluding that current design methods tend to over-predict capacity. Pham and Hancock [26], through a series of 24 physical tests, also observed substantial reductions in shear strength, in some cases approaching 74%.

Despite the increasing use of CFS in structural systems, the specific behaviour of members containing web openings remains insufficiently explored. The available design guidance, particularly within AISI S100 [21], appears unconservative for perforated members, and Eurocode provisions currently offer no explicit rules addressing shear in such elements. Although Pham and Hancock [26] proposed strength equations, their formulation was based on a relatively limited set of specimens. This highlights the need for a broader and more systematic investigation into how opening geometry and section characteristics influence shear capacity across a wider parameter range.

The present study aims to fill this gap. Detailed finite-element models were created in ABAQUS CAE 2017 [25], incorporating both material nonlinearity and geometric imperfections, and were calibrated against the experimental results reported by Pham and Hancock [26]. After validation, these models were used to conduct a comprehensive parametric study exploring the effects of opening size and shape, as well as web slenderness, on shear response and associated failure modes. Insights from this analysis were then used to propose and evaluate a design expression for estimating the shear strength of perforated CFS members.

The methodology

To investigate the shear behaviour of CFS members with web openings, validated FE models were developed in ABAQUS CAE 2017 [25], incorporating material and geometric nonlinearities. These models were calibrated using the experimental data by Pham and Hancock [26].

The experimental setup comprised 24 back-to-back lipped channel specimens tested at the University of Sydney [26], including 19 with square web openings (40–120 mm) and 5 control specimens (Fig. 1). Each beam had a 450 mm span with a 200 mm shear span and was tested under three-point bending. Section dimensions were 202 × 18 × 77 mm, with thicknesses of 1.5, 1.9, and 2.4 mm. Openings were waterjet cut, and flange distortion was mitigated using bolted angle straps, while shear was induced via bolted T-plates [26].

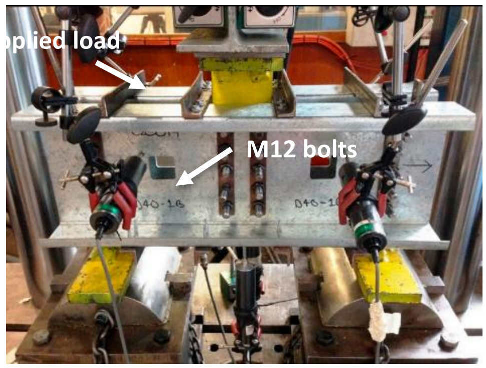

Figure 1. Experimental arrangement used for testing CFS channel sections containing web openings.

A bilinear stress–strain model was adopted with an elastic modulus of 194 GPa, a strain-hardening slope of E/100, and ν = 0.3. Yield and ultimate strengths were $f_{\mathrm{y,0.2\%}} = 486$ MPa and $f_{\mathrm{u}} = 578$ MPa, respectively [26]. Supporting plates were modelled as elastic with $E = 210$ GPa.

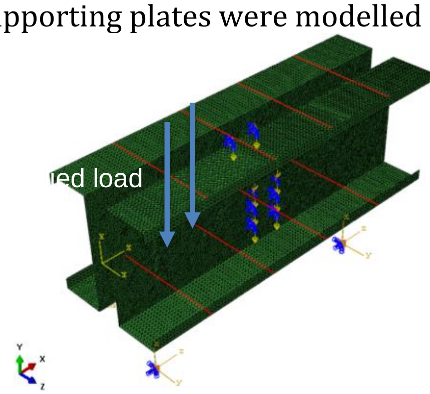

Figure 2. Modelling of the tested CFS back-to-back channel member in FE ABAQUS [17]

Loading and support conditions mirrored the physical setup. Web bolts were modelled using “Beam” elements [25] with a 12 mm circular section (Fig. 2). Load was applied at mid-span to a virtual bolt group. Supports were simulated using coupled reference points with “Connector” and “Coupling” constraints [25] to represent rollers and transfer loads.

The FE models were built using the S3R formulation from the ABAQUS element library [25], which is a three-node triangular shell element with reduced integration. This option was selected because it captures the behaviour of thin steel plates effectively, including the small amount of transverse shear that remains significant in moderately thick regions of the section. As the plates become thinner, this shear component diminishes naturally. Several trial meshes were tested to balance run time with solution accuracy, and a uniform element size of roughly 6 mm was ultimately adopted, as it provided stable results without unnecessary computational cost.

The role of initial out-of-plane imperfections in thin-walled cold-formed members is well established, as they can influence both the onset of buckling and the peak load a member can sustain [27-37]. To reflect this behaviour, all models were assigned an imperfection amplitude of 0.15 t, where t denotes the plate thickness. The shape of each imperfection pattern was obtained by first carrying out an eigenvalue buckling analysis in ABAQUS to extract the corresponding mode shape. This mode shape was then scaled to the prescribed magnitude and superimposed on the base geometry before running the nonlinear analyses.

The FE models were verified using a nonlinear post-buckling analysis based on the RIKS arc-length method [25], demonstrating strong correlation with both the experimental load-displacement responses (see Fig. 3). The average discrepancies observed were approximately 3% for peak shear resistance and 5% for initial stiffness. Specimens either without web openings or with relatively small ones (e.g., S19-040) exhibited abrupt shear buckling following the peak load. In contrast, those with larger openings (e.g., S19-120) experienced early onset of local buckling and displayed more gradual, ductile behaviour beyond the peak load.

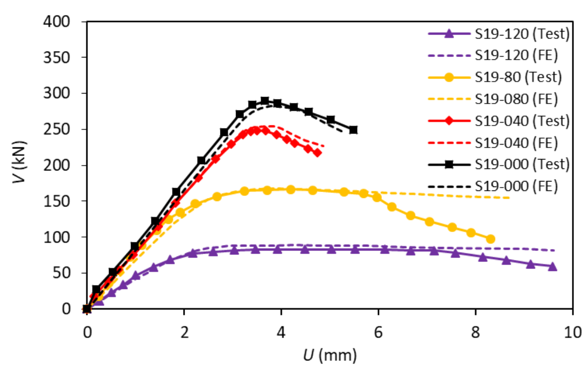

Figure 3. Shear-displacement (V-U) from FE models and tests [26]

For members without openings (S19-000) or with small openings (S19-040), the load-displacement response was nearly linear up to a distinct peak, followed by a sharp drop due to shear buckling. In contrast, members with larger openings (S19-080 and S19-120) showed early signs of yielding or local buckling near the openings, resulting in a less linear response. Their peak load was reached with a plateau, followed by a more gradual and ductile unloading phase.

To examine how web perforations affect the shear response of CFS members, an extensive parametric programme was carried out using 136 FE simulations. The model set was arranged to explore the main geometric factors thought to influence behaviour: the size of the opening, its shape, and the slenderness of the web. Both square and circular perforations were included so that differences in buckling patterns and load–deformation characteristics could be captured. For the circular openings, an equivalent square dimension was calculated using the relationship $d_h = 0.825D_h$, following the approach outlined by Pham and Hancock [26], where $D_h$denotes the hole diameter. Of the total simulations, 80 represented sections with square openings, and the remaining 56 used circular ones, with all specimens analysed under shear-critical conditions.

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The opening dimensions used in the study ranged from no perforation at all to a maximum size of 160 mm, increasing in increments of 10 mm to capture a broad set of practical configurations. For clarity in interpreting the results, the ratio d_h/h, with $h = 202$mm representing the clear web depth, was used to classify the openings into three groups: small ($d_h/h < 0.2$), medium ($0.2 \leq d_h/h \leq 0.5$), and large ($d_h/h > 0.5$). Variations in web slenderness were introduced by adjusting the plate thickness while keeping the web height unchanged, producing h/t values corresponding to five commercially available thicknesses: 1.2, 1.5, 1.9, 2.4, and 3.0 mm. Selecting these sizes allowed the study to bridge gaps left in earlier research. This parametric arrangement provided the basis for assessing how shifts in geometry and thickness influence ductility, stiffness, and shear strength, ultimately supplying the information needed to develop a practical design approach for perforated CFS webs.

Findings/Discussion

Figure 4 illustrates how the normalised shear capacity V_u/V_0 changes as the opening ratio d_h/h increases for beams with various web slenderness values h/t. In this context, $V_u$denotes the peak shear resistance of the perforated member, while V_0 represents the corresponding value for a member without openings. The quantity V_u/V_0, commonly described as the shear reduction factor q_s, offers a straightforward way to adjust the solid-web design predictions for use with perforated sections. The discussion that follows examines how both opening size and web slenderness shape the overall shear response, including the behaviour beyond the peak load.

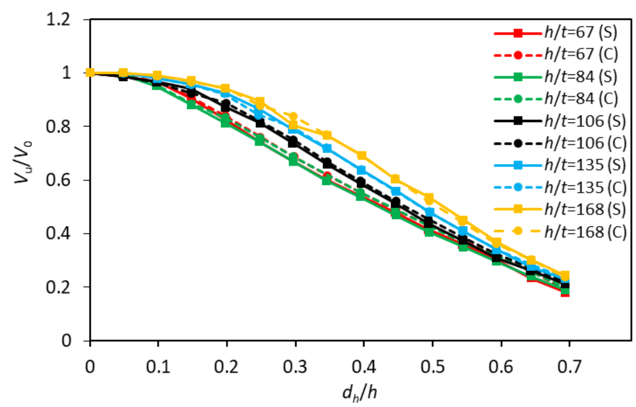
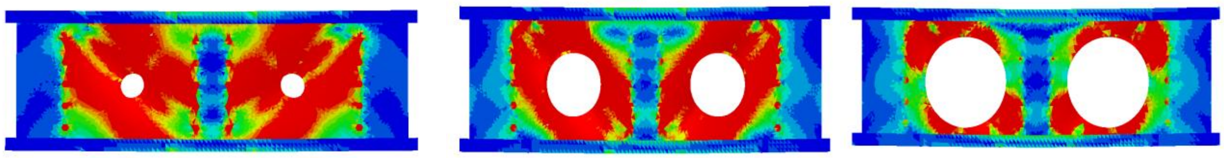


Figure 4. Variation of normalised shear capacity (V_u/V_0) with web opening ratio (d_h/h) for CFS beams of differing web slenderness (h/t), comparing specimens with square (S) and circular (C) openings [17]

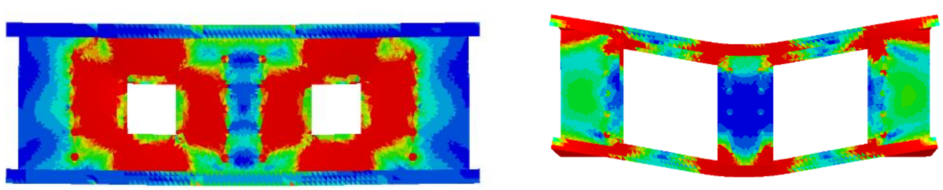
As shown in Fig. 4, increasing the size of the web opening leads to a clear downward trend in shear capacity for all considered values of web slenderness, with the curve developing a characteristic double-curvature form. When the openings are small ($d_h/h < 0.2$), the reduction in strength remains modest, generally less than about 20%. In the mid-range ($0.2 \leq d_h/h \leq 0.5$), the loss of capacity becomes more progressive and follows an almost linear pattern. Once the opening extends beyond roughly half of the web depth, the reduction becomes substantial, and the ultimate strength may fall by as much as 80%. This highlights the need for caution when large penetrations are introduced, as they can severely undermine the section's ability to resist shear. Fig. 5 illustrates the corresponding buckling shapes and Von Mises stress fields from the FE models for beams with circular openings of different sizes. For the smallest openings, the behaviour is governed by diagonal shear buckling accompanied by the formation of a tension field (Fig. 5a). With larger holes, however, yielding and localised buckling develop at the edges of the perforations (Figs. 5b and 5c), mirroring the pronounced drop in shear resistance observed in the numerical results.



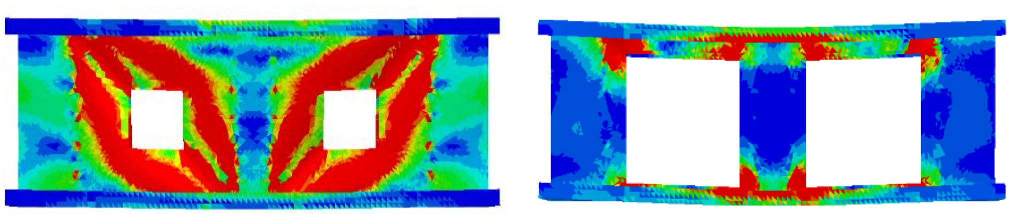
(a) $d_h/h = 0.2$ (b) $d_h/h = 0.39$ (c) $d_h/h = 0.59$

Figure 5.Buckling shapes and Von Mises stress distributions obtained from FE models of CFS beams with various circular opening sizes [17]

Figure 6 shows that the normalised shear capacity V_u/V_0 declines as the web becomes less slender—that is, as the h/t ratio decreases. The magnitude of this reduction depends strongly on the opening ratio d_h/h, with the influence becoming much more pronounced when the openings are of medium or large size. For members with small perforations, reducing the slenderness from 135 to 67 results in only a modest drop of roughly 12% in V_u/V_0. When larger openings are present, the same change in slenderness can reduce shear strength by as much as 20%. The post-peak Von Mises stress distributions in Fig. 6 illustrate this behaviour for different combinations of slenderness and opening size. Beams with higher slenderness, meaning relatively thin webs, develop noticeable tension field action (TFA), which enhances their ability to carry shear. Thicker webs, represented by lower h/t ratios, tend not to form a well-defined tension field and instead show earlier yielding, which explains the overall reduction in performance.



(a) $h/t = 67$, $d_h/h = 0.35$ (b) $h/t = 67$, $d_h/h = 0.69$



(c) $h/t = 168$, $d_h/h = 0.35$ (d) $h/t = 168$, $d_h/h = 0.69$

Figure 6. Buckling modes and Von Mises stress contours for CFS beams featuring various combinations of web slenderness and opening dimensions [17]

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Conclusion

This study examined how CFS members behave in shear when their webs contain openings and the implications for design. Nonlinear FE models that included both material yielding and initial imperfections were created and checked against available test results. After validation, the models were used in a broad parametric investigation to assess how factors such as stiffness, strength, and failure patterns influence shear response. From these outcomes, a practical strength expression for perforated sections was developed and compared with predictions from current design provisions, including AISI S100-16. The investigation confirmed that increasing the size of web openings consistently led to reduced shear capacity, independent of opening shape. For small openings ($d_h/h < 0.2$), strength reductions remained modest, not exceeding 20%. However, as the opening size increased ($0.2 \leq d_h/h \leq 0.5$), the strength declined more linearly. Openings exceeding half the web depth ($d_h/h = 0.5$) resulted in up to 80% loss of shear strength. Additionally, reducing the web slenderness (h/t) further diminished the shear capacity, particularly in members with medium to large openings. Sections with higher slenderness benefited from TFA, enhancing their resistance, while thicker webs (lower slenderness) primarily yielded without significant TFA contribution.

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Поведение стальных элементов холодной штамповки с отверстиями в перемычках при изгибе при сдвиге

Аннотация. Профили из холодногнутой стали (CFS) стали широко применяться в современном строительстве, поскольку обеспечивают высокую прочность при малом весе и простоте монтажа. Однако при выполнении отверстий в стенке профиля для размещения инженерных коммуникаций характер восприятия сдвиговых усилий может существенно измениться. В данной работе подробно исследуется поведение швеллерных профилей с такими отверстиями. Была разработана серия нелинейных конечно-элементных (FE) моделей, в которых учитывались начальные геометрические несовершенства, а полученные численные результаты сравнивались с доступными экспериментальными данными для подтверждения их физической достоверности. После валидации модели использовались для анализа влияния различных параметров, включая форму отверстия, его размер и гибкость стенки, на сдвиговую несущую способность. Численные результаты показывают резкое снижение несущей способности при увеличении размеров отверстий или при повышенной гибкости стенки. В наиболее неблагоприятных случаях наблюдалось снижение до 90% из-за размера отверстия и примерно на одну треть — из-за гибкости стенки.

Ключевые слова: холодногнутая сталь; потеря устойчивости при сдвиге; отверстие в стенке; конечно-элементное моделирование; швеллерный профиль.

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Қабырға ойықтары бар суықтай иілген болат элементтерінің жаншу-тұрақсыздық (shear buckling) мінез-құлқы

Аңдатпа. Суықтай иілген болат (CFS) профильдері қазіргі құрылыс саласында кеңінен қолданылады, себебі олар жеңіл әрі орнатуға оңай бола тұра, айтарлықтай беріктікке ие. Алайда инженерлік коммуникацияларды өткізу үшін профильдің қабырғасына ойықтар жасалғанда, оның жаншу-срез күштерін қабылдау қабілеті едәуір өзгеруі мүмкін. Бұл жұмыста мұндай ойықтары бар арналық (channel) профильдердің мінез-құлқы жан-жақты зерттелді. Алдын ала геометриялық кемшіліктері ескерілген бірқатар сызықтық емес ақырлы элементтер (FE) модельдері құрылып, олардың нәтижелері қолда бар эксперименттік деректермен салыстырылып, физикалық шынайылығы тексерілді. Валидациядан кейін модельдер ойықтың пішіні, өлшемі және қабырға жіңішкелігінің (slenderness) жаншуға қарсы беріктікке әсерін зерттеу үшін қолданылды. Сандық нәтижелер ойықтың үлкен болуы немесе қабырғаның тым жіңішке болуы беріктікке айтарлықтай әсер ететінін көрсетеді. Ең қолайсыз жағдайларда ойық өлшеміне байланысты беріктік шамамен 90%-ға дейін, ал қабырға жіңішкелігіне байланысты шамамен үштен бір бөлігіне дейін төмендеген.

Түйінді сөздер: суықтай иілген болат; жаншу тұрақсыздығы; қабырға ойығы; ақырлы элементтер моделдеуі; арналық қима.

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