



## **Buckling analysis of lipped CFS clip angles in beam-column connections enabling reuse**

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### **Abstract**

Bolted Cold-Formed Steel (CFS) clip angles are commonly employed as a connection method for connecting CFS beams with columns. In this research, 2-bolted lipped clip angles are used to connect 900 mm-long CFS beams with a 1330 mm-long hot-rolled Square Hollow Section (SHS) column. The parameters investigated in this experimental study include bolt diameter (10 mm and 12 mm), thickness of the clip angles (1.5 mm, 2.0 mm and 2.5 mm) and aspect ratio of the clip angles (0.357, 0.2 and 0.147), totalling 18 full-scale experiments. Primarily, two failure modes were observed - i. local buckling of clip angles in the leg connected to the beam web; ii. Tearing failure of the clip angles in the leg connected to the column flange. Based on the experimental study validated by AISI S100, the aspect ratio limit is suggested to classify the connections based on the failure mode. Suggestions for the reusability of clip angles and CFS beams are also provided from a reuse point of view within the scope of the current experimental study.

### **1. Introduction**

Cold-formed steel (CFS) has emerged as a transformative material in modern construction due to its lightweight nature, cost-effectiveness, and high strength-to-weight ratio. CFS sections, manufactured from thin galvanised sheets through roll forming, are ideally suited for light-frame residential construction, modular systems, and prefabricated assemblies. The efficiency of CFS production, combined with its amenability to factory-based fabrication, positions it as a key enabler of industrialised construction. However, the thinness of CFS introduces susceptibility to local buckling under concentrated loads, necessitating careful consideration in member and connection design.

Connections are critical to structural performance as they govern load transfer, overall ductility, and the feasibility of disassembly and reuse. In CFS structures, clip angle connections are prevalent for several reasons, like ease of installation and inherent potential for demountability in modular

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assemblies. Unlike welded connections, bolted clip angles can be disassembled without damaging the primary structural members, a feature highly valued in the context of the circularity in construction (CIC).

Historically, design standards such as AISI S100 and AS/NZ 4600 have focused on screw-attached clip angles, where self-drilling or self-tapping screws connect the clip angles to the beams. These provisions are relatively well-documented in the literature (Selvaraj and Madhavan, 2020, 2021a, 2021b), with failures typically governed by screw pull-out, bearing deformation, or angle fracture. The abundance of screw-connection data reflects practical market dominance that screwed assemblies are rapid to deploy and suitable for low- to medium-load applications. In contrast, bolted clip angles are underrepresented in design guidelines, despite offering distinct advantages. Bolted connections have comparatively higher initial stiffness, load capacities and more stable load-deformation response than their screwed counterparts. They offer enhanced rotational capacity in moment-dominated applications. From a demountability perspective, it is easier to disassemble and enable reuse than with screwed connections.

Early experimental work by Natesan and Madhavan (2019) examined shear strength and parametric sensitivity to bolt diameter, but tested only narrow geometric ranges and did not explore the clip angle aspect ratio. More recently, Pham et al. (2022) and Mallepogu and Madhavan (2023) provided comprehensive parametric data on combined shear-moment response, confirming that clip angle slenderness (aspect ratio) significantly affects moment-rotation behaviour and fracture mode, with slender angles exhibiting reduced rotational capacity and brittle failure. However, this work remains limited in scope regarding ultimate moment capacity under pure moment-dominated loading and does not address design for reusability.

Design methods based on existing codes (e.g., Eurocode 3 Part 1.8, AISC 360) can estimate shear capacity using component-based approaches, but often neglect local buckling and bearing deformation in thin sections, leading to unconservative or overly simplified predictions. The result is a critical gap: limited experimental data specifically targeting moment-dominated bolted CFS clip-angle connections, no established design guidance accounting for aspect ratio effects on failure mode transition, and absent recommendations for assessing reusability and circular design.

The construction industry accounts for approximately 30% of global waste generation and consumes vast quantities of virgin materials annually. In response, the European Union's Circular Economy Action Plan (2020) and similar initiatives worldwide now mandate or incentivise circular design principles: designing buildings and components for disassembly, reuse, and material recovery (Jeyabalan et al., 2023, 2025a, 2025b; Umaraj et al., 2025a, 2025b; Selvaraj and Chan, 2024). Steel, with its indefinite recyclability and high scrap value, is well-positioned to support circular strategies. However, realising circular benefits requires not only recyclability, but design for disassembly and reuse of whole components or assemblies.

CFS systems offer particular promise for circular construction:

- **Modularity:** Prefabricated CFS frames can be assembled and disassembled with minimal labour and equipment.

- Reversible fastening: Bolted connections enable demountability without destroying primary members.
- Portability: Lightweight sections simplify transport and relocation to new projects.
- Factory quality: Controlled manufacturing and quality improve structural reliability and inspection capability.

Despite these advantages, current practice rarely designs CFS connections with explicit reusability criteria in mind. Standardised testing and design methods focus on strength and stiffness for initial service, not on residual capacity after damage, damage classification, or assessment protocols for determining whether a connection can be reused, refurbished, or must be replaced. This shortfall represents both a technical gap and a sustainability opportunity. For clip angle connections specifically, the lack of clarity on failure modes under moment bending and how different modes affect remaining capacity creates uncertainty for designers and building operators considering reuse scenarios. The main objectives of this study are as follows.

- Experimentally investigate the moment-dominated CFS clip angle connections and characterise the failure mode across the parametric range, including bolt diameter, clip angle thickness and clip angle aspect ratio.
- Identify the aspect ratio threshold that governs the transition between failure modes.
- Quantify parametric effects on initial stiffness and ultimate capacity
- Provide preliminary design guidelines for the reuse of bolted CFS clip angle connections.

## **2. Experimental Programme**

This section outlines the material property tests, experimental setup, instrumentation, loading protocol and specimen preparation.

### *2.1 Material property tests:*

Tensile coupon specimens were extracted from the cold-formed steel channels and sheets used to fabricate the clip angles and tested in accordance with ASTM E8 standard specifications. Testing was conducted on an Instron Universal Testing Machine (UTM) at the Industrial Centre, The Hong Kong Polytechnic University, to establish the material properties required for subsequent analysis.

The coupon specimens were carefully prepared with rectangular cross-sections and appropriate gauge lengths as specified in ASTM E8. Dimensional measurements, including thickness, width, and gauge length, were recorded at multiple locations using precision instruments to ensure accuracy. Two strain gauges were attached to each specimen to capture elongation during loading. Tests were performed at room temperature under displacement control at a constant strain rate until specimen fracture occurred. Load and elongation data were continuously recorded, from which engineering stress-strain curves were generated.

The key material properties obtained from the coupon testing program are summarised in Table 1. The measured Young's modulus values ranged from 204 to 207 GPa, which is consistent with typical values for cold-formed steel. The yield strength and ultimate tensile strength reflect the properties of the cold-formed steel material used in the clip angles and beam sections. The elongation at fracture demonstrates adequate ductility of the material, typical of cold-formed steel exhibiting gradual yielding followed by strain hardening.

Table 1: Summary of Material Properties

Plate thickness (mm)	Yield Stress, $f_y$ (MPa)	Young's Modulus, $E$ (GPa)	Ultimate Stress, $f_u$ (MPa)
1.5	307.2	204	371.09
2	312.4	205	373.48
2.5	314	207	374.30

All values reported are mean values of 3 coupon tests

### 2.2 Specimen preparation:

The test specimens comprised a built-up beam assembly connected to a fixed column via lipped clip angles. This section describes the fabrication and assembly of the principal components. Two identical cold-formed steel channel sections were positioned back-to-back and screwed to form an I-section. Cold-formed steel lipped clip angles of three nominal thicknesses (1.5 mm, 2 mm and 2.5 mm) were used to connect the CFS beams to the hot-rolled column. Each clip angle incorporated 2 rows of pre-punched holes to accommodate 10 mm and 12 mm diameter bolts. In addition, three different aspect ratios of clip angles were selected. The above-mentioned variables of three parameters contributed to a total of 18 specimens. The clip angles were bolted to the web of the beam and column flange using high-strength bolts and washers to establish proper bearing contact without distorting the thin-walled sections. The hot-rolled steel square hollow section (SHS 100×100×10) was rigidly fixed to the testing frame using bolts. This arrangement simulated the constraint imposed by a column base in practical structures, providing the fixed-base boundary condition typical of frame-to-foundation connections. The CFS beam was free to rotate at the other end. All specimens underwent comprehensive dimensional verification prior to testing. Thickness measurements were recorded at multiple locations on each clip angle to account for variations in the cold-forming process. Geometric properties, including leg dimensions, hole positions, and overall dimensions, were documented using calibrated measurement instruments. Cross-sectional properties of the beam and clip angle sections were calculated from the measured dimensions to provide accurate geometric input for subsequent analysis.

### 2.3 Test setup:

The experimental setup consisted of a hot-rolled column fixed to the testing frame in the Structural Engineering Laboratory at The Hong Kong Polytechnic University. The beams used for all the tests are 900 mm-long CFS channels connected back-to-back using two rows of staggered screws at 100 mm spacing. All the experimental parameters pertained to the clip angles connecting the CFS beams to the SHS column. A total of 18 experiments were conducted, encompassing three parameters, namely, bolt diameter, clip angle thickness and clip angle aspect ratio. As can be seen in Fig. 1, a manually controlled vertical load was applied on the beam at a relatively higher lever arm of 720 mm, making the experiments moment-dominated. The instrumentation involved two LVDTs. LVDT 1 was used at the point of application of vertical load to measure the corresponding vertical deformation, and LVDT 2 was placed in line with the end of the cantilever leg of the clip angle to measure the clip angle deformation.

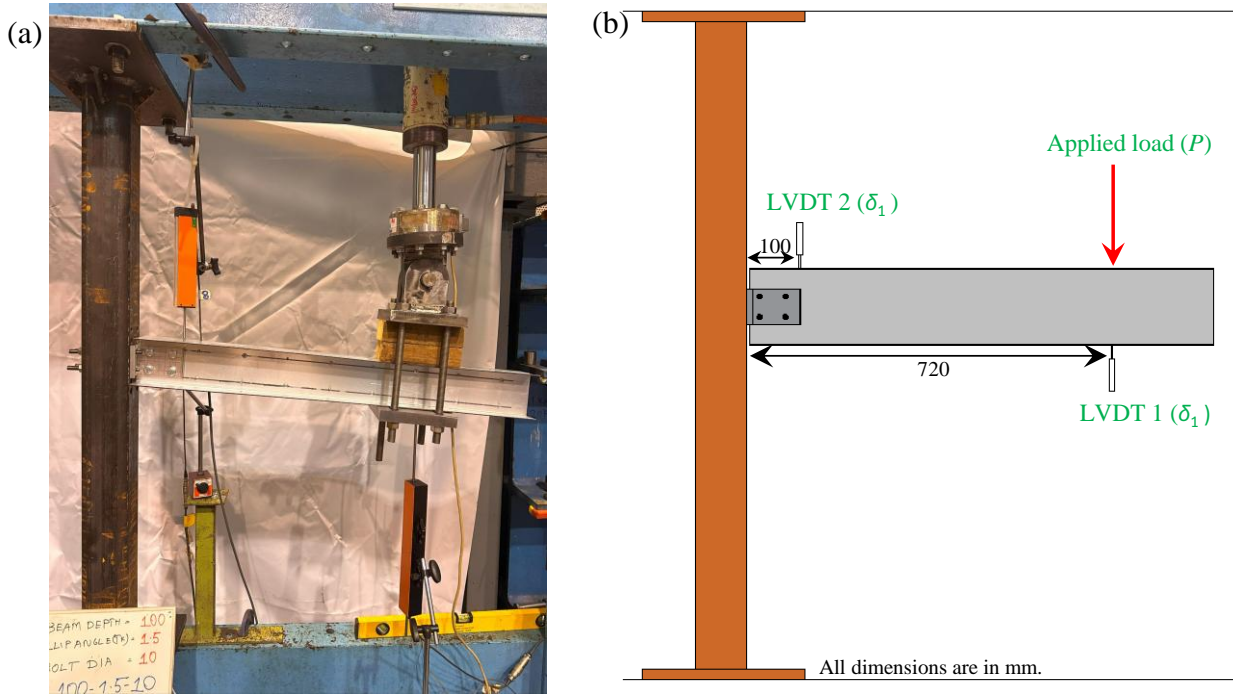


Figure 1: (a) Test set up photograph; (b) Instrumentation

### 3. Results:

#### 3.1 Load-Displacement Response and General Behaviour:

All 18 specimens exhibited progressive load-deformation behaviour characteristic of semi-rigid connections in cold-formed steel construction. The connections were loaded such that the loading is stopped when the compression flange of the beam touches the column. The rationale behind this was to analyse the isolated capacity of clip angle, as the beam will contribute when the beam touches the column. In general, there were two different types of responses - 1. Initial elastic phase followed by gradual stiffness degradation marked by local deformations in clip angle; 2. Initial elastic stiffness phase and an increase in stiffness due to the contact of the beam compression flange to the column. Figure 2 presents representative load-displacement curves for selected specimens, illustrating the influence of key geometric parameters on overall response. The curves reveal that thicker clip angles and larger bolt diameters resulted in steeper initial slopes (higher stiffness) and higher ultimate loads. Conversely, specimens with larger aspect ratios demonstrated lower initial stiffness and reduced ultimate capacity.

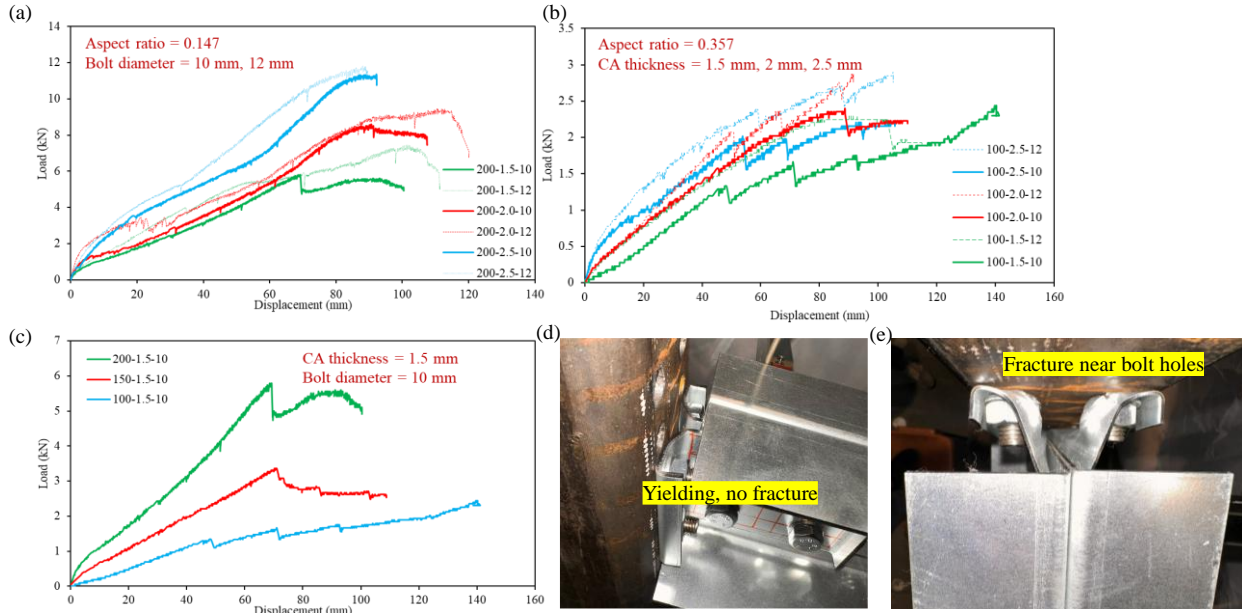


Figure 2: (a) Effect of clip angle thickness; (b) Effect of bolt diameter; (c) Effect of aspect ratio; (d) Mode A failure (yielding-dominated); (e) Mode B failure (fracture-dominated)

Qualitative observations during testing confirmed that most specimens demonstrated ductile response with substantial deformation capacity prior to ultimate failure. Progressive yielding and local deformations were visible during loading, with damage initiation and failure locations varying systematically with specimen geometry. Early-stage failure markers such as localised buckling, bearing deformation at bolt holes, and incipient cracking were evident in the load-displacement records as subtle changes in slope or non-linearity in the curve.

Table 2 summarises the key experimental results for all 18 specimens, presenting ultimate load and the initial elastic stiffness. The table reveals consistent trends: specimens fabricated with thicker sections (2.5 mm) and larger bolts (12 mm) consistently achieved higher loads and stiffness values compared to their slender (1.5 mm) and smaller-bolt (10 mm) counterparts. The effect of aspect ratio is equally evident, with lower aspect ratios (0.147) producing superior performance across all thickness and bolt diameter combinations.

Table 2: Summary of Test results

Specimen	Bolt dia (mm)	Thickness (mm)	Aspect Ratio	Ultimate Load (kN)	Initial Stiffness (kN/mm)
S1	10	1.5	0.357	1.93	0.51
S2	12	1.5	0.357	2.30	0.64
S3	10	2	0.357	2.40	0.74
S4	12	2	0.357	2.76	0.83
S5	10	2.5	0.357	2.21	1.24
S6	12	2.5	0.357	2.90	1.1
S7	10	1.5	0.208	3.36	1.05
S8	12	1.5	0.208	3.82	1.33
S9	10	2	0.208	5.11	1.66
S10	12	2	0.208	4.51	1.93
S11	10	2.5	0.208	5.11	2.3
S12	12	2.5	0.208	4.60	2.62

S13	10	1.5	0.147	5.80	2.28
S14	12	1.5	0.147	7.45	2.25
S15	10	2	0.147	8.6	2.62
S16	12	2	0.147	9.48	2.99
S17	10	2.5	0.147	11.04	3.68
S18	12	2.5	0.147	11.82	3.96

### 3.2 Observed Failure Modes:

Post-test examination of all 18 specimens revealed two principal failure modes, with some specimens exhibiting a combination of both. The dominant failure behaviour in any given specimen depended primarily on the aspect ratio and thickness of the clip angle, with secondary influence from bolt diameter. The identification and classification of these modes is central to understanding connection behaviour and forms the basis for reusability assessment presented in later sections.

#### Mode A: Buckling-dominated response (Yielding and local buckling):

Buckling-dominated response was the predominant failure mechanism in specimens with larger aspect ratios and thicker sections. This mode encompassed two sub-behaviours: initial local yielding of the clip angle material, which progressed into more pronounced local buckling of the clip angle leg connected to the beam web. The failure initiated as localised plastic deformation, typically in the region adjacent to or between the bolt holes of the beam-web leg. As loading progressed, the initially subtle yielding developed into out-of-plane waviness and pronounced local buckling. The buckling pattern was generally symmetric about the clip angle plane, with plastic hinging concentrated in the central span between the two bolt rows.

Localised yielding was evident around bolt holes used to attach the clip angles to the column. Specimens exhibiting this failure mode did not experience fracture or tearing of the material. Figure 2 (d) shows a representative specimen exhibiting Mode A failure. The out-of-plane deformation and local buckling are clearly visible, with the clip angle leg displaced perpendicular to its original plane. Post-failure inspection confirmed that the clip angle material, though plastically deformed and locally buckled, remained intact without net-section fracture. The bolt holes showed evidence of bearing deformation, but no cracking or tearing was observed.

#### Mode B: Fracture-dominated response (Tearing and net-section fracture):

Fracture-dominated response was the dominant mechanism in specimens with smaller aspect ratios and thinner sections. In these cases, the clip angle was more slender in the vertical load-carrying direction, creating higher local demands at the bolt line. The failure mechanism combined localised buckling with net-section tearing at the anchored leg connected to the column flange. Failure initiated as plastic deformation concentrated at the top bolt hole, where the clip angle is subjected to tension. Stress concentrations at the bolt hole edges, combined with the reduced cross-sectional area in the net section (the ligament between adjacent bolt holes), created conditions favourable for crack initiation and rapid propagation. The fracture originated at the edge of a bolt hole and propagated rapidly across the net section. Figure 2 (e) shows a representative specimen exhibiting Mode B failure. Once initiated, the crack advanced suddenly, with load-carrying capacity dropping sharply.

The transition between Mode A (yielding-dominated) and Mode B (fracture-dominated) was primarily controlled by the aspect ratio ( $b/d$ ) of the clip angle. Deeper clip angles (smaller  $b/d$ ) are

more slender in the vertical load-carrying direction and experience higher local demands at the bolt line for a given applied moment. Specimens with  $b/d \geq 0.25$  exhibited predominantly Mode A yielding-type behaviour without net-section fracture. Specimens with  $b/d \leq 0.21$  transitioned toward Mode B tearing, with combined buckling and fracture mechanisms active. The intermediate range ( $0.21 < b/d < 0.25$ ) showed transitional behaviour, with both mechanisms contributing.

Clip angle thickness provided a secondary influence on the failure mode: thicker sections (2.5 mm) consistently favoured Mode A buckling over Mode B, likely due to the increased bending stiffness that reduced local stress concentrations at bolt holes and enabled more distributed load transfer. Thinner sections (1.5 mm) were more prone to Mode B tearing, particularly at lower aspect ratios. Bolt diameter showed minimal direct influence on failure mode classification, though 12 mm bolts slightly improved bearing performance and modestly delayed tearing initiation compared to 10 mm bolts.

### *3.3 Parametric Influence on Strength and Stiffness:*

The experimental results reveal systematic trends in connection strength and initial stiffness as functions of clip angle thickness, bolt diameter, and aspect ratio. Increasing thickness from 1.5 mm to 2.5 mm consistently enhanced both ultimate load capacity and initial stiffness across all bolt and aspect ratio combinations. Thicker sections provide greater bending rigidity and distribute bearing stresses more effectively at bolt holes, delaying net-section tearing and enabling higher capacity. Average improvements were approximately 20% (1.5 to 2.0 mm) and 30% (1.5 to 2.5 mm) in ultimate load, with similar trends observed in initial elastic stiffness. These gains were consistent across parametric ranges, confirming thickness as a robust design parameter. Upgrading from 10 mm to 12 mm bolts improved the ultimate capacity and initial stiffness. Larger bolts reduce bearing stress concentrations and increase load transfer stability. This effect was secondary to thickness but inconsistent across all configurations for ultimate load.

Aspect ratio had the largest influence on both strength and stiffness. Deeper clip angles (smaller  $b/d$ ) exhibited higher ultimate loads and greater initial stiffness, yet were more susceptible to fracture-dominated failures. Ultimate loads increased monotonically with decreasing aspect ratio, from approximately less than 2.5 kN ( $b/d = 0.357$ ) to 5 kN ( $b/d = 0.208$ ) to more than 7.5 kN ( $b/d = 0.147$ ), representing approximately more than 200% increase in capacity as aspect ratio decreased from 0.357 to 0.147. Initial stiffness also exhibited similar growth trend. Figure 2 (c) illustrates this upward trend, demonstrating the mechanical advantage of deeper clip angles in resisting applied moment.

However, this strength advantage came with a cost. Deeper clip angles experienced combined buckling and tearing (Mode B), whereas shallower angles failed by yielding alone (Mode A). This reflects the geometry of the connection: deeper angles produce larger bending curvatures and higher stress concentrations at the bolt line in the anchored leg, eventually triggering net-section fracture despite higher overall load capacity. The practical implication is that strength should not be the sole criterion for design. While deeper angles are mechanically stronger, they approach or enter the fracture-dominated regime, which has adverse consequences for reliability and reusability. The transition occurs near  $b/d \approx 0.21$ – $0.25$ , where the failure mode shifts from yielding-controlled to fracture-prone.

## 4. Discussion:

### 4.1 Aspect-ratio-based Failure Mode Classification:

The test results show that the aspect ratio of the clip angle, expressed as  $b/d$  (horizontal leg width to vertical depth), is the dominant geometric parameter governing the transition between yielding-dominated and fracture-dominated behaviour. Across all thicknesses and bolt diameters, specimens with  $b/d = 0.357$  (shallowest angles) consistently failed in a yielding-dominated manner. These connections developed their capacity through distributed yielding and local buckling of the leg, without net-section tearing at the anchored leg. Similarly, specimens with  $b/d = 0.147$  (deepest angles) increasingly exhibited combined buckling and tearing in the anchored leg. Although these configurations achieved higher ultimate loads and stiffness (Section 3.3), the concentrated tensile demand at the bolt line led to net-section fracture once local ductility was exhausted. The data therefore support an aspect-ratio boundary that separates deformation-controlled and fracture-controlled behaviour. When the aspect ratio is  $> 0.25$ , failure is governed by yielding and local buckling, while failure is governed by net-section tearing in the anchored leg when the aspect ratio is  $< 0.2$ . An aspect ratio value between 0.2 and 0.25 can be considered as the transition zone where both failure modes are observed. In such cases, thickness determined the failure mode. Within the scope of the present geometry and loading, this classification provides a practical aspect-ratio limit for failure-mode prediction: larger  $b/d$  values favour ductile, deformation-governed response, while smaller  $b/d$  values, although stronger, are more prone to fracture.

### 4.2 Reuse implications:

The two principal failure modes have very different consequences for the reusability of clip angles and associated members. A practical assessment can be based on both the observed damage pattern and the deformation demand at the connection. In North American practice, a deformation limit of approximately 3.2 mm (1/8 in.) is commonly adopted as a serviceability criterion for clip-angle connections. Deformations significantly beyond this level indicate that the connection has operated well above typical service conditions and has likely experienced substantial inelastic action. This code-based limit provides a rational benchmark for judging whether a clip angle could be considered for reuse.

For connections failing in Mode A (yielding and local buckling, typically at higher  $b/d$  values, the clip angle remains continuous, with damage concentrated in localised plastic hinges and plate buckling near the bolt rows. In this case, no tearing or visible cracking is present at or emanating from the bolt holes. The deformation of the clip angle at the 3.2 mm serviceability limit was also minimal. The component may be considered a candidate for reuse, either under reduced design actions in the same structure or in another application. In such cases, reuse should be conditional on a simple inspection protocol: visual examination for cracking, measurement of residual offsets, and verification that new bolts will bear properly in the existing holes. If required, a simple proof test in the new configuration can provide additional assurance.

In contrast, connections failing in Mode B (tearing and net-section fracture, typically at lower  $b/d$ ) exhibit complete or partial rupture of the anchored leg. The load path through the clip angle is severed, and the corresponding deformations are far beyond any serviceability consideration. Clip angles showing net-section tearing, through-thickness cracks at bolt holes or severe bolt-hole elongation should be classified as non-reusable. Such components can only be recycled as scrap steel; structural deployment is not realistic. The CFS beams in the present tests generally

experienced limited damage, with distress concentrated in the clip angles and immediate bolt regions. Provided that the beam web and flange at the connection do not show significant crippling, local buckling, or severe hole elongation, the beams themselves can typically be reused with new clip angles, subject to standard inspection.

## 5. Conclusions:

An experimental investigation of 18 bolted lipped clip-angle connections was conducted to characterise structural behaviour under moment-dominated loading and assess implications for circular design and reusability. The test program systematically varied clip angle thickness (1.5, 2.0, 2.5 mm), bolt diameter (10, 12 mm), and aspect ratio ( $b/d = 0.147, 0.208, 0.357$ ) to examine parametric effects on strength, stiffness, and failure modes. The main conclusions are:

1. Specimens with  $b/d \geq 0.25$  exhibited yielding-dominated behavior with the clip angle remaining structurally continuous, while those with  $b/d \leq 0.21$  experienced combined buckling and net-section tearing of the anchored leg. A transition zone exists near  $b/d \approx 0.21-0.25$ .
2. Despite higher ultimate loads and stiffness at lower aspect ratios (up to 200% increase from  $b/d = 0.357$  to  $0.147$ ), these configurations are more susceptible to net-section fracture due to concentrated tensile demand at the bolt line. This decoupling between strength and failure robustness is a critical design consideration.
3. Connections failing in Mode A (yielding and local buckling) retain structural continuity and, provided deformations are of the order of the 3.2 mm serviceability limit, are candidates for reuse after inspection. Connections failing in Mode B (net-section tearing) are non-reusable and must be replaced.

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