A comprehensive review and classification of inter-module connections for hot-rolled steel modular building systems

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Abstract. In the recent history the development of inter-module connection (IMC) systems for steel modular building systems (MBSs) has gained traction with many researchers and engineers being in pursuit of universally performant connection systems. Even though many of the newly proposed connections are presented as potential disruptors for the market, it rarely is the case as it is a difficult, if not impossible task, to deliver a "fit-for-all" design given the complex and multi-dimensional character of this topic. While recently, there have been numerous review studies concerned with IMCs for hot-rolled steel MBSs, most of them focused only on a limited number of existing connections, while also failing to preserve a consistency in nomenclature and classification methods. Considering the large and growing volume of published studies which investigate IMCs for hot-rolled steel MBSs, there is a pressing need to classify all systems under a unified naming convention based on a systematic classification and thus harmonise the literature and promote a well-structured development of future designs.

The present study gathered sixty IMCs from the literature and proposed a nomenclature using a rigorous and consistent classification based on the method of joining. Complementary tables with all relevant studies published on each connection system are constructed, providing a comprehensive review of the existing literature at the time and helping to guide the development of future studies in an effort to promote a unified approach. In order to identify "must-have" features and key areas of improvement for future IMC designs based on the advantages and limitations of existing connections, a multi-attribute ranking system is developed and employed. The adoption of the proposed ranking system has the potential to facilitate the improvement of future designs, as well as to enhance existing connections in low-scoring areas, serving as a useful decision-making tool for both researchers and practitioners concerned with this topic.

Keywords: inter-module connections, modular building systems, hot-rolled steel MBS, demountability, reusability, multi-attribute ranking, seismic resilience, damage control

1. Introduction

Modular construction belongs to the category of Modern Methods of Construction (MMC) and is often generically used in industry or academia as a hypernym for terms such as Modular Integrated Construction (MiC), Prefabricated Building Systems (PBS), Integrated Building Systems (IBS) or Modular Building Systems (MBSs), embodying the seamless integration of elemental, panelised and volumetric units into fully finished buildings.

For the purpose of this study, modular construction and its aforementioned analogues adhere to SCI's [1] definition, referring to the highest levels of Off-Site Construction (OSC) hierarchy (Fig. 1) (Level 3 OSC according to Gibb [2] and Lawson et al. [3] or Level 4 OSC according to Goodier and Gibb [4]), where pre-engineered, fitted-out and serviced "building blocks" are stacked and attached to one another to form the structural frame of the completed building. Fig. 1 below illustrates the three main types of structural elements that can form the structural framing of a building, each representing a different level of OSC. Some classifications also consider non-structural volumetric pods (e.g., toilet or bathroom applications) as an additional level of prefabrication. In this research project, non-structural pods are considered to be a sub-category of volumetrics (Level 3 OSC), while the term volumetric unit or module refers exclusively to the load-bearing element that constitutes a part of the structural framing of an MBS.

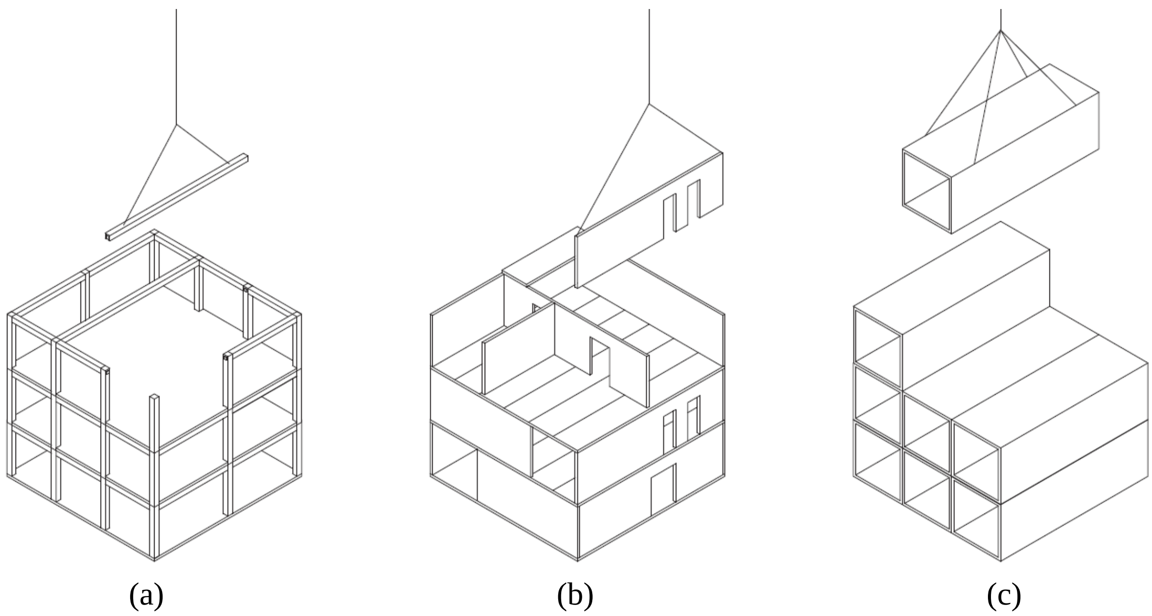

Fig. 1. Hierarchy of OSC: (a) elemental, (b) panelised, (c) volumetric [5]

So far, volumetric modular construction has adopted a wide range of structural materials (Fig. 2) for its chassis, which have been typically divided in the literature [3,6–8] into timber, concrete, steel (cold-formed and hot-rolled), composite or a combination of these.

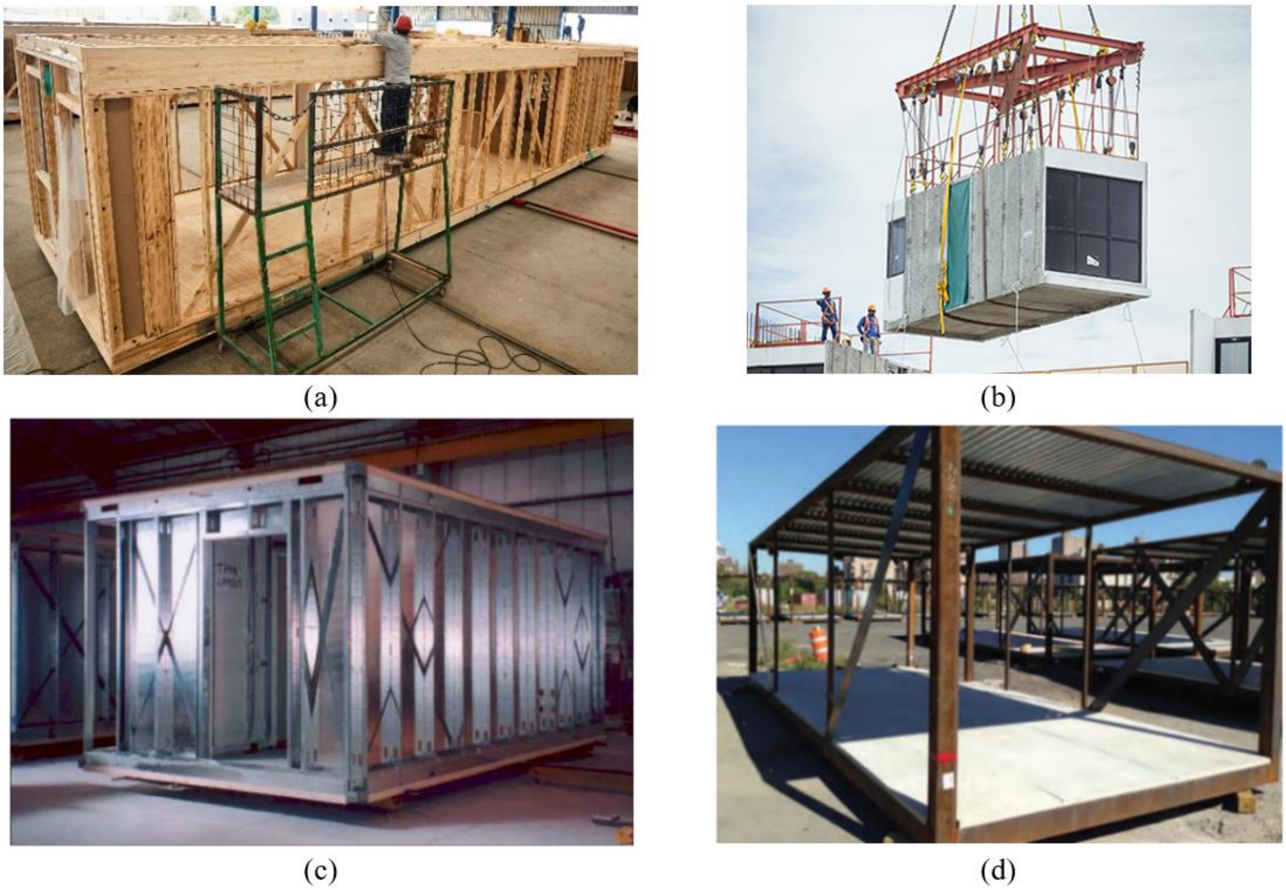

Fig. 2. Types of modules based on structural framing material: (a) Timber [9], (b) Concrete [10], (c) Light-gauge steel [11], (d) Hot-rolled steel [12]

The choice of material is usually governed by the height and structural system of the building, with timber and light-gauge steel typically used in low-to-mid-rise applications (Fig. 3) due to their limited strength and lateral load capacity [3,13].

(a) (b)

Fig. 3. Low- and mid-rise MBSs: (a) 6-storey cross-laminated timber (CLT) modular building [14], (b) 3-storey light-gauge steel pods structure [15]

In Fig. 4, the tallest five MBSs in the world are presented, while additional data about these projects is available in Table 1. From these projects, it is suggested that concrete and hot-rolled steel PPVC are the preferred types of modules when it comes to achieving high-rise MBSs.

(a) (b) (c) (d) (e)

Fig. 4. Tallest modular buildings using PPVC: (a) Collins House [16], (b) Croydon Tower [17], (c) Atira La Trobe [18], (d) Clement Canopy [19], (e) Atlantic Yards B2 [20]

When it comes to fully modular high-rise MBSs, effects of wind and seismic loads intensify and generate larger shear and tension forces in the connections between modules. Due to the limited strength and stiffness exhibited by existing inter-module connections (IMCs), fully modular MBSs are only adopted for low-rise applications. For MBSs with four to ten storeys, stable structural systems are achieved by stiffening the internal panels of modules to enable diaphragm action or by means of braced frames located at stairs and gable walls, while taller MBSs require more robust solutions such as reinforced concrete/steel-plated cores or podium structures to provide lateral stability [21,22].

Looking at the projects in Table 1, it must be stressed that while concrete or hybrid modular units like HBS are efficiently used in some of the tallest modular buildings, the use of wet joints is a downside of such technologies, being completely against the core principles of modular construction such as adaptability, demountability, replaceability, and reusability. In this regard, hot-rolled steel modules like those used in the Atlantic Yards B2 and Croydon Tower display bespoke advantages such as: better strength-to-weight ratios, lighter overall structures (Atlantic Yards B2 project was 65% lighter than its concrete counterparts [12]), greater architectural flexibility, improved wastage control and better overall sustainability [23]. Above all, the use of dry joints (i.e., mechanical connections) between the steel building units offers great opportunities for easy deconstruction and potential for reuse, which makes MBSs made of corner-supported hot-rolled steel volumetrics the scope of the present study.

Table 1. Tallest modular buildings using PPVC

#	Project	Year	Location	Height (storeys)	Superstructure system
1	Collins House	2019	Australia	184 m (60 storeys)	14-storey in-situ RC podium + 472 Hickory Building System (HBS) structural and façade modules
2	Croydon Tower	2020	UK	135.6 m (44 storeys)	In-situ RC core + 546 Vision Modular Systems (VMS) modules
3	Atira La Trobe	2018	Australia	131 m (44 storeys)	Prefab RC core and shear walls + 285 HBS modules
4	Clement Canopy	2019	Singapore	129.5 m (40 storeys)	RC core + 1899 concrete modules
5	Atlantic Yards B2	2016	US	98.2 m (32 storeys)	Structural steel plinth, braced frames, transfer girder, hat truss and 2 tuned-mass dampers (TMDs) + 930 steel modules

To date, numerous studies [6,7,24–28] have reviewed the performance of prefabricated modular buildings, with several focusing on the structural behaviour of multi-storey/high-rise modular structures [8,29–33]. There is a consensus among researchers that IMC systems are paramount in the structural performance of steel MBSs, many emphasising the lack of reliable connections between modules as a crucial limitation. Due to the absence of design codes for steel modular construction, current practice follows guidelines for conventional structural steelwork or sea freight containers, which often produces overestimations in design calculations, or on the contrary, fails to account for more complex scenarios, specific to modular structural systems. This is due to the discrete nature of connectivity in steel modular structures (i.e., using corner-supported hot-rolled steel volumetric units) which induces additional stresses in the connections between modules and sometimes creates complex stress paths. For mid-to-high-rise steel MBSs, the effect of these additional stresses cumulates with the large tension and shear forces experienced due to intense lateral loads (i.e., wind, earthquake) and can severely impact the overall safety of the structure in terms of strength and stability.

In the past decade, the development of IMC systems for hot-rolled steel MBSs has gained traction with many researchers and engineers being in pursuit of universally performant connection systems. Even though many of the newly proposed connections are presented as potential disruptors for the market, it rarely is the case as it is difficult - if not impossible - to deliver a “fit-for-all” design given the complex and multi-dimensional character of this topic. On this note, several studies [34–37] highlighted the following limitations in MBSs made of hot-rolled steel: inefficient load-transfer paths between modules affecting the ability to display rigid diaphragm behaviour (revealed by measuring the diaphragm service stiffness [38]), poor ductility, failing to meet the American Special Moment Frame (SMF) [39] or the European Moment Resisting Frame (MRF) [40] seismic design provisions, and the necessity to meet manufacturing (complexity of parts and offsite integration processes) and constructional (ease of assembly/disassembly) requirements besides structural demands. The context of the ongoing climate emergency has brought forward the link between circular economy (CE) and opportunities of hot-rolled steel MBSs for disassembly and reuse [41] but the necessity for using hybrid structural systems and the functionality of IMCs question the actual prospects of deconstruction.

In an overview of the structural performance of modular buildings Lacey et al. [7] summarised the works on a total of eighteen IMCs, assessing their ability to provide vertical and/or horizontal connectivity. A more general overview of advancements, challenges and opportunities of multi-storey modular buildings was offered by Ferdous et al. [29], including four IMC systems and highlighting the potential of developing reliable interlocking connections. Lacey et al. [35] reviewed twelve bolted IMCs and assessed the stiffness properties of four of them based on the experimental, numerical and theoretical studies available in the literature. Srisangeerthanan et al. [37] reviewed the performance of twenty-four IMCs based on three main criteria (structural, constructional, and manufacturing), revealing that self-alignment, self-locking, ease of disassembly and undemanding processes of pre-attaching connection parts to modules were among the most challenging requirements for the existing designs. Deng et al. [31] drew attention to the seismic performance of steel MBSs, identifying thirty connections in the literature and insisting on the necessity to carry out more studies in order to develop a more robust knowledge about their seismic design. Thai et al. [30] highlighted an extremely low application of modular construction in high-rise buildings and illustrated fifteen connections, partly attributing the hesitation and lack of confidence felt among construction professionals about this technology to the lack of strong inter-module joining techniques. Chen et al. [8] summarised the recent advancements of structural systems, design techniques and illustrated more than thirty IMCs, insisting also on the importance of manufacturing and constructional aspects such as ease of manufacturing, ease of installation, particularly the difficulties of fixing the fourth modular unit at the internal joint due to lack of access. Rajanayagam et al. [42] and Nadeem et al. [43] focused on some of the existing IMCs and emphasised the role of automated and semi-automated joints in solving constructional challenges in MBS. Most recently, Lacey et al. [44] have focused on the experimental setups used to test the mechanical properties and failure modes of IMCs by classifying the test configurations into three main levels, analysing the efficiency of these setups for different types of frames (braced/unbraced), and providing insightful recommendations regarding the applicability of each type of experiment.

While recently, there have been numerous review studies concerned with IMCs for hot-rolled steel MBSs, most of them focused only on a limited number of the existing connections, while also failing to preserve a consistency in nomenclature and classification methods. Considering the large and growing volume of published studies which investigate IMCs for hot-rolled steel MBSs, there is a pressing need to centralise all systems under a unified naming convention based on a systematic classification in order to organise the literature and promote a well-structured development of future designs. The present study gathered sixty IMCs from the literature and proposed a nomenclature using a rigorous and consistent classification based on the method of joining and where the joining technique was too general (i.e., bolted joints), the system was further divided in sub-categories based on the connected elements. The main advantages of this classification stem from its consistency all-throughout based on joint typologies, providing a harmonised overview of the existing literature. Also, the scalability of the system facilitates its adoption and further expansion as new connections are proposed. Additionally, complementary tables with all relevant studies published on each connection system were constructed, providing a concise overview of the existing literature at the time and helping to guide the development of future studies in lacking directions.

In order to identify "must-have" features and key areas of improvement for future IMC designs based on the advantages and limitations of existing connections, a newly developed multi-attribute ranking system is proposed, based on the three core criteria used by Srisangeerthanan et al. [37], namely, structural, manufacturing and constructional performance attributes. While the new system is based on the same three categories for its metrics, the scale and marking criteria have been completely re-structured by adopting a more holistic perspective based on qualitative analysis and engineering intuition. Additionally, characteristics such as design resilience through re-centring and energy dissipation, reusability and design flexibility were not explicitly considered in the metrics of the previous study and were thus included in the present review. Plotting the total scores in the form of stacked bar charts was not intended to suggest that the top scoring connections are best-for-all solutions, but rather facilitated the visualisation and identification of promising connection systems or areas for improvement. Moreover, the plethora of new connections developed recently support the need for the present review, which amasses sixty IMCs, being a very complete, focused and up-to-date study. All in all, the adoption of the proposed ranking system has the potential to facilitate the development of future designs, as well as to improve existing connections in low-scoring areas, serving as a useful tool for both researchers and practitioners concerned with this topic.

2. State-of-the-art inter-module connections (IMCs)

In the following section the wide and often tangled literature of IMCs for hot-rolled steel MBSs has been systematically re-organised, having drawn attention to some of the key features for each of these systems to facilitate a comprehensive critical appraisal.

A common technique of joining modular building blocks is to rigidly connect them using wet (grouted) or welded joints (Fig. 5) or by means of adhesive bonds. While this type of joints may be able to craft rigid structural framings (displaying both vertical and horizontal diaphragm rigidity), enhancing the lateral stability of the building, their main disadvantage is that deconstruction is greatly (if not completely) impeded, wasting one of the inherent qualities of modular construction. Given that the direction of the present research seeks to achieve sustainable MMC, such joints were omitted from further consideration due to their monolithic nature.

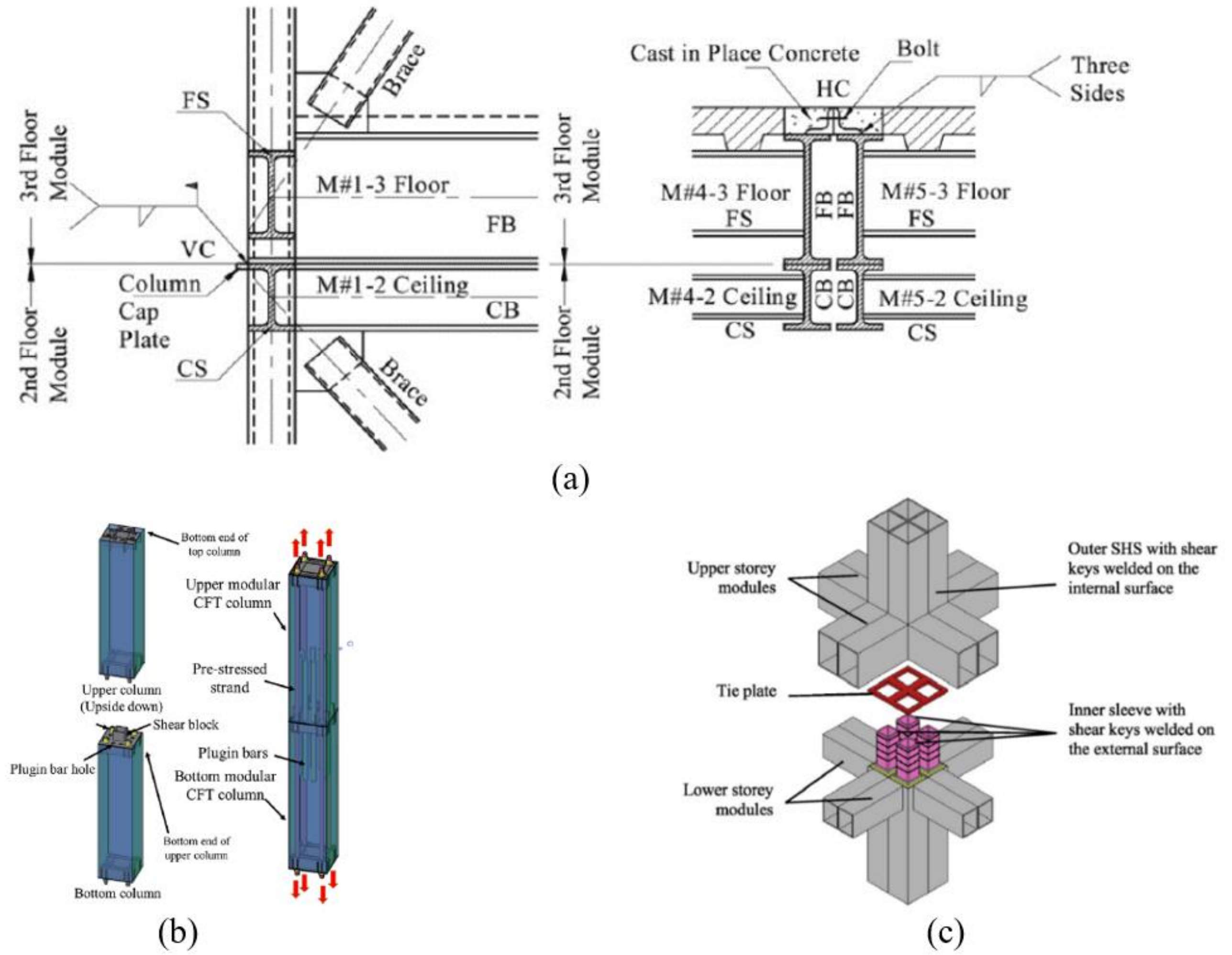

Fig. 5. Rigid IMCs: (a) welded and cast-in-place [45,46], (b) pre-stressed in-situ concrete-filled [47], (c) grouted-sleeve [48,49]

The rest of IMCs were classified and labelled under three main categories (Fig. 6), based on the main coupling method: locking devices (**LD01-07**), through post-tensioned rods (**PT01-06**), and three typologies of bolted joints (**CTC01-16, BTB01-12, FTF01-19**). Additionally, complementary to the classification, five tables were built (**Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**), summarising all the experimental, numerical and analytical studies done so far about the existing IMCs, which identify the types of frame setups, the scales of the experiments, the software used, the types of analyses carried out and the design considerations developed. The experimental works have been classified into small-scale and meso-scale, where 'small-scale' refers to test setups designed to study the localised behaviour at connection level, while 'meso-scale' refers to larger joint assemblies which include partly or wholly the joining members such as beams and columns and even entire modules in some particular cases. The same classification was done for numerical works, with the addition of simplified joint models which are usually developed and used to study the structural behaviour of entire buildings at global level. These tables serve as a concise and comprehensive overview of the literature and can be useful in guiding future studies in specific areas with a lack of data. The numerous cells marked with N/A (not available) represent data which was either not developed or which was not available in the public domain at the moment of writing.

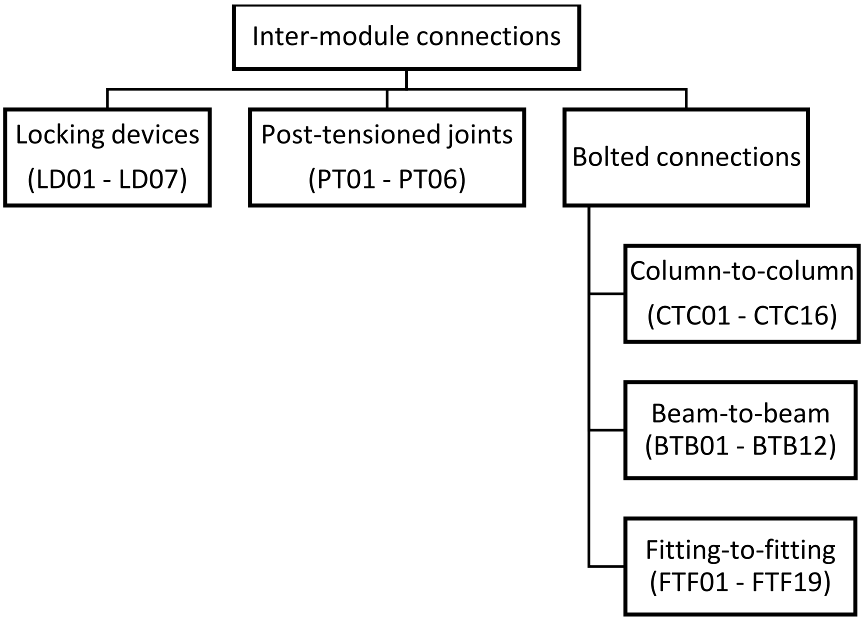

Fig. 6. Classification of IMCs

2.1. IMCs with locking devices

Seven innovative IMCs were identified in this category, listed in Table 2**.** In general, these joints use either tool-driven or gravity-actioned mechanisms as showed in Fig. 7.

Table 2. IMCs with locking devices

ID code	**Type of locking device**
LD01 [50]	Twistlock
LD02 [51]	Interlocking grooves
LD03 [52]	Rotary device and screwed nut
LD04 [53]	Self-locking plug-in device
LD05 [54]	Torque-activated pin device
LD06 [55]	Self-locking spring-activated tabs
LD07 [56]	Self-locking spring-activated sliding blocks

The generic twist lock connection (**LD01**) is the standard joint for freight containers and it comes in a great variety of forms (i.e. bottom tier, between tiers, automatic, midlock) [50]. Such systems are highly practical, engineered for numerous assembly/disassembly workflows and designed to resist strong lateral forces (i.e., those experienced on the decks of barges), hence their adoption for relatively low-rise buildings. However, the tightness and tolerance levels achieved using these connections are far from the ones required in taller applications.

Based on the Modular Integrating System (MIS) concept, Sharafi et al. [51] devised a quick and easy-to-install self-locking mechanical joint for corner-supported modules (**LD02**). Unique strips with tongues and grooves secure the integrating connection into a continuous modular structure, yet adhesives are indispensable for achieving effective uplift resistance. Chen et al. [52] introduced a rotary IMC (**LD03**) suitable for mid-rise buildings, which houses connector devices inside corner fittings. The connectors facilitate the installation and engagement/disengagement operations, but they provide limited bending stiffness. A clever plug-in self-locking connector (**LD04**) was developed by Dai et al. [53], securing the inter-module joint by the tight clenching of latches to the ring-teeth of a stud and friction between the latches and an overlaying cone. Other self-locking devices (**LD06, LD07**) were engineered using spring-activated mechanisms [55,56] which greatly reduce the need for human intervention during on-site installation. Despite the convenience of automatic locking mechanisms, this type of connectors consists of a very large number of complex individual components, putting a strain on the supply chain. Among the latest innovations in functional IMC systems is the device (**LD05**) introduced by Srisangeerthanan et al. [54]. Integrated in the cast corners of the modules, a driven torque mechanism actioned by a tool slid through the SHS column translates a set of pins, interlocking the internal and external components. Nevertheless, the novel system requires high-precision manufacturing, struggling to accommodate large tolerances induced by geometric imperfections.

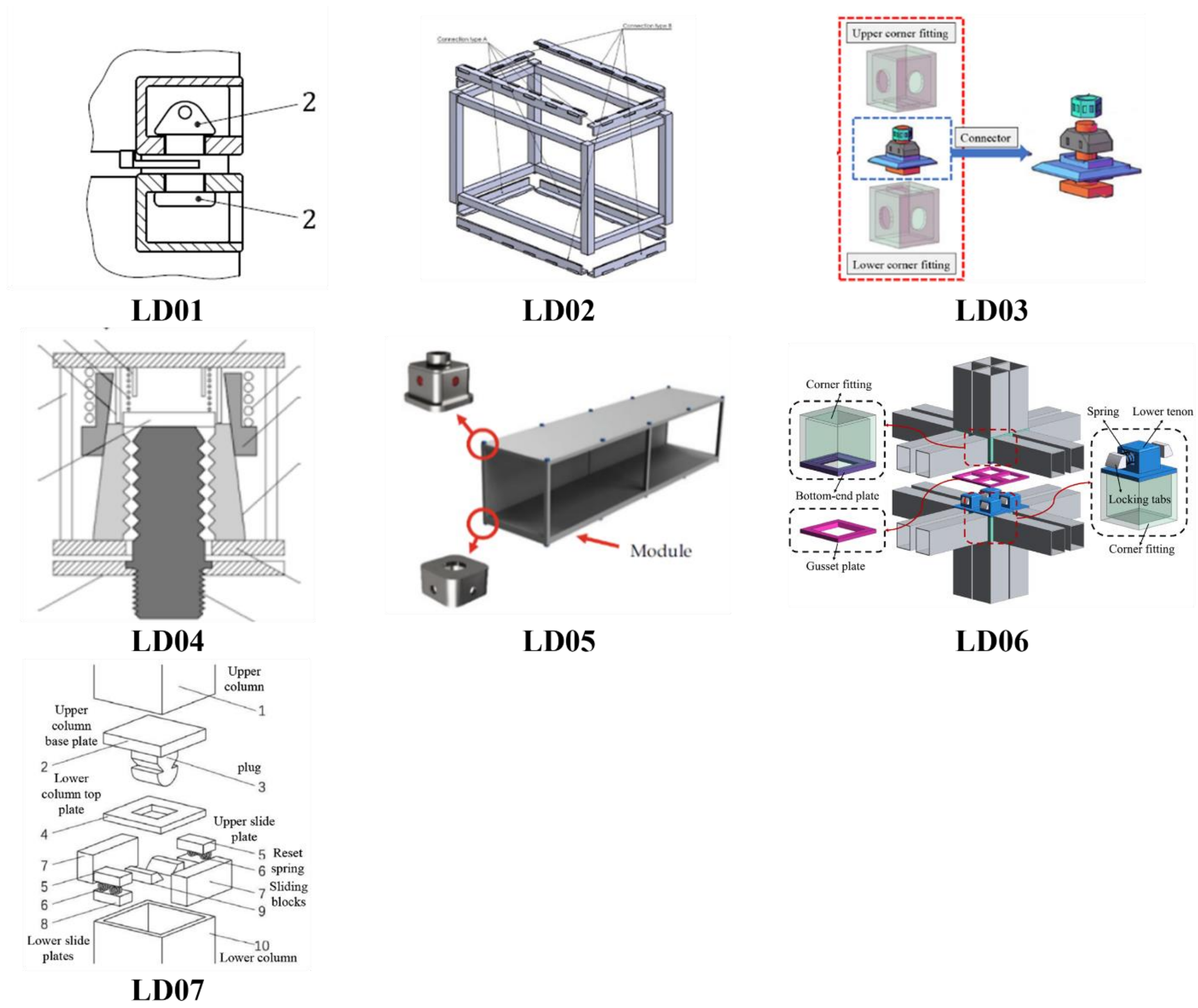

Fig. 7. **IMCs with locking devices: LD01 [50], LD02 [51], LD03 [52], LD04 [53], LD05 [54], LD06 [55], LD07 [56].**

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Index	Experimental		Numerical			Analytical
			Detailed			
	Small-scale	Meso-scale	Small-scale	Meso-scale	Simplified joint model	
LD01	N/A	N/A	N/A	N/A	N/A	N/A
LD02	N/A	N/A	N/A	N/A	Connector elements; Abaqus; Three-storey 3D frame; Static/Dynamic horizontal loads; Notional Module Removal; [51]	N/A
LD03	Tension/ Shear/ Bending; [52,57]	Two-storey two-sided 2D frame; Monotonic/ Cyclic lateral load; [58]	3D Solid (C3D8R); Abaqus; Tension/ Shear/ Bending; [52,57] 3D Solid (C3D8R); Abaqus Tension/ Bending; [59]	3D Solid (C3D8R); Abaqus; One-storey, two-sided 2D frame; Monotonic lateral load; [59] 3D Solid (C3D8R); Abaqus Two-storey one-sided 2D frame; Cyclic lateral load; [60]	Connector elements; Abaqus; One-storey, two-sided 2D frame; Monotonic lateral load; [59]	Mechanical model; Connection design formulae; [52,57] Mechanical model [58,60]
LD04	Tension; [53]	One-storey one-sided 2D frame; Monotonic/Cyclic vertical load; [53]	N/A	3D Solid (C3D8R/C3D20R); Abaqus; One-storey one-sided 2D frame; Monotonic vertical load; [61]	N/A	Connection design formulae; [53]
LD05	N/A	N/A	N/A	N/A	N/A	N/A
LD06	N/A	One-storey one-sided planar frame; Cyclic vertical load [55]	N/A	3D Solid (C3D8R); Abaqus; One-storey one-sided 2D frame; Cyclic vertical load; [55]	Connector elements; Abaqus; One-storey one-sided 2D frame; Cyclic vertical load; [55]	Mechanical model; Connection design formulae; [55]
LD07	N/A	N/A	N/A	N/A	N/A	N/A

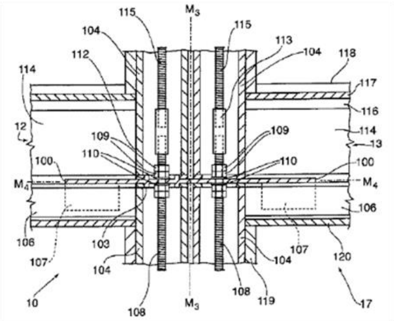
2.2. Post-tensioned IMCs

By and large, post-tensioned (PT) IMCs (Table 3) consist of rods inserted at the corners of modules through hollow sections (most of the times running continuously throughout the entire height of the columns). Where applicable, continuity of the bars is ensured by couplers or sleeve nuts, while nuts tighten the rods to connecting plates, which are often enhanced by shear keys of various geometries (Fig. 8).

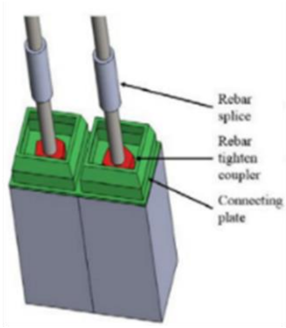
Table 3. Post-tensioned IMCs

ID code	Coupling method
PT01 [62]	PT rods running through SHS columns
PT02 [34]	PT rods clamped with nuts through shear keys
PT03 [63]	PT rods coupled through steel boxes
PT04 [64]	PT rods coupled through shear keys with access openings
PT05 [65]	PT rods coupled through shear keys
PT06 [66]	PT rods running through SHS columns

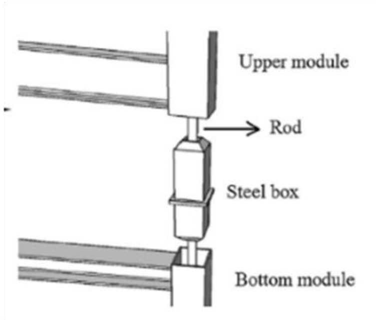
Farnsworth [62] patented an internal IMC (**PT01**) with threaded tension rods coupled by sleeve nuts and regular tension bolts. Although module alignment and installation are facilitated by annular setting pins, additional post-tensioning tasks slow down on-site construction time when compared to all-bolted connections. Other details of PT IMCs (**PT02-06**) enhanced the local stiffness of the joint by inserting steel-boxes/shear keys at the ends of SHS columns, interlocking with the profiles of the hollow sections [34,63–66]. Assembly difficulties and safety concerns caused by on-site post-tensioning remain a major disadvantage, while access openings introduce weak regions in critical locations.



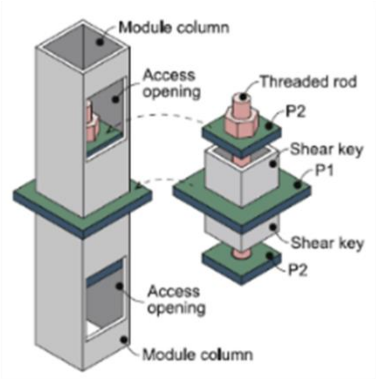
PT01



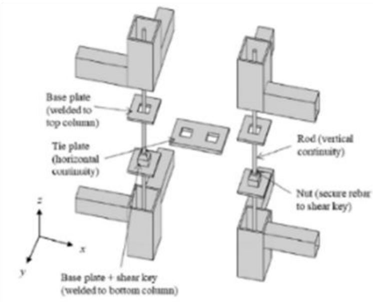
PT02



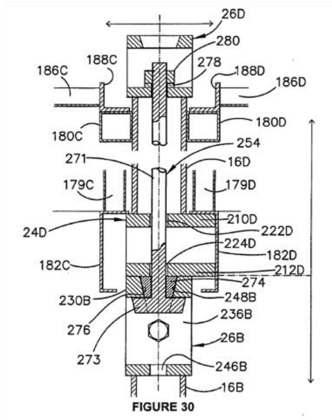
PT03



PT04



PT05



PT06

Fig. 8. Post-tensioned IMCs: PT01 [62], PT02 [34], PT03 [63], PT04 [64], PT05 [65], PT06 [66].

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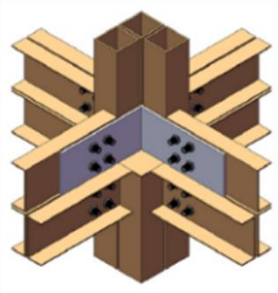
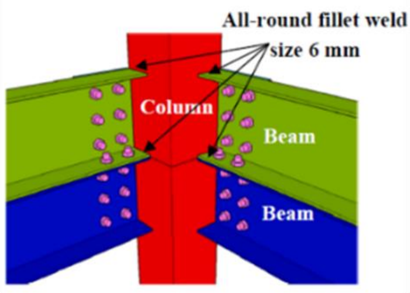
Index	Experimental		Numerical			Analytical
			Detailed		Simplified joint model	
	Small-scale	Meso-scale	Small-scale	Meso-scale		
PT01	N/A	N/A	N/A	N/A	N/A	N/A
PT02	N/A	N/A	N/A	N/A	N/A	N/A
PT03	N/A	One-storey one-sided 2D frame; Cyclic lateral load; [63]	N/A	N/A	N/A	N/A
PT04	Shear; [64]	N/A	3D Solid (C3D8R); Abaqus; Shear; [64]	3D Solid (C3D8I); Abaqus; Two-storey two-sided 2D frame; Pushdown analysis; Column removal; [67]	Link elements; SAP2000; Six-storey 3D frame; Horizontal Equivalent Static Force; Response-Spectrum Analysis; Time History Analysis; [68]	Mechanical model; Connection design formulae; [69] Progressive collapse design formulae; [67]
PT05	N/A	N/A	N/A	3D Solid (C3D8R); Abaqus Two-storey two-sided 2D frame; Column removal; [70]	Link elements; ETABS; 40-storey 3D frame; Pushdown Analysis; Column removal; [65,71] Link elements; SAP2000; 5 to 30-storey 2D frames; Pushdown Analysis; Nonlinear Dynamic Analysis; [70]	N/A
PT06	N/A	N/A	N/A	N/A	N/A	N/A

2.3. Bolted IMCs

Bolted IMCs are by far the most diverse of the three categories, with a wide variety of typologies. In essence, these joints use common and easy-to-manufacture steel parts such as corner fittings, plates, bolts, screws, nuts, washers, and other additional components like pins, tenons, spigots, or even rubber layers (Fig. 9,



BTB01



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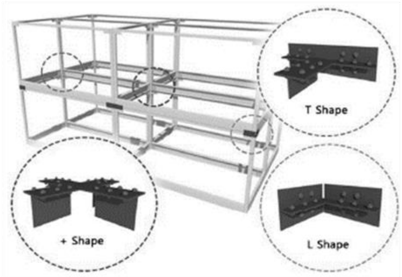

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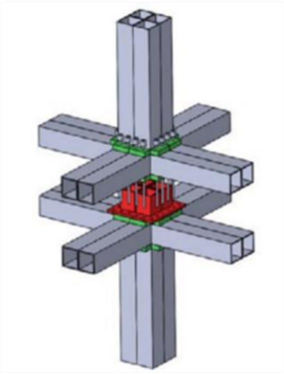
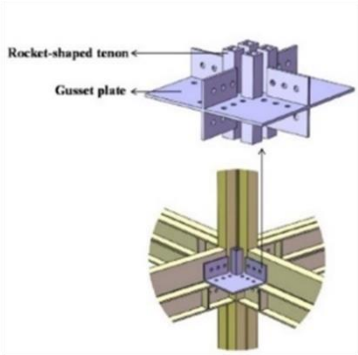
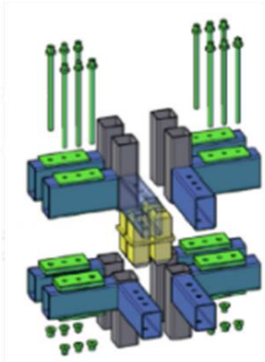


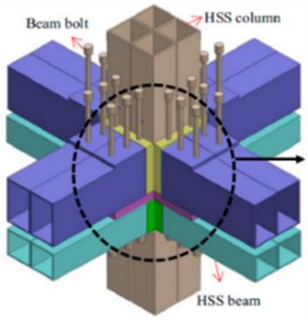
BTB04



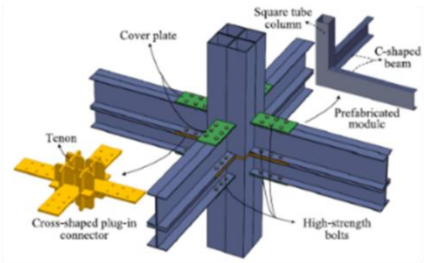
BTB05



BTB06



BTB07



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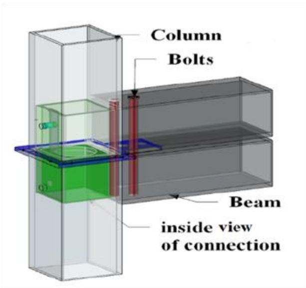
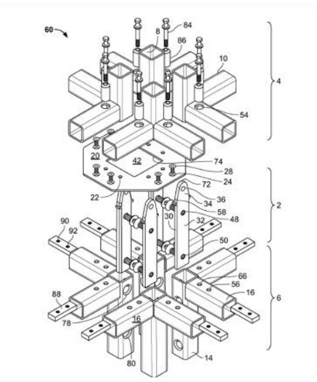


BTB09



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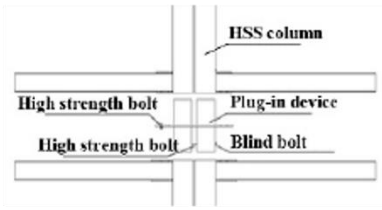
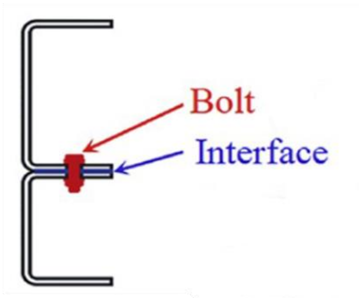


BTB11



BTB12

Fig. 10, and Fig. 11). Due to the multitude of existing configurations, these connections were further split into smaller groups based on characteristic features by which each system can be identified.

2.3.1. Column-to-column (CTC) connections

The most common typology of bolted IMCs are column-to-column joints (Table 4) derived from classic splice joints for tubular sections, with plates which are welded to the ends of the hollow sections and clamped together by bolts (Fig. 9).

Table 4. Column-to-column bolted IMCs

ID code	Joint typology
CTC01 [72]	Vertical endplates and horizontal tie plates
CTC02 [73]	Up-down I beams
CTC03 [74]	Cover plate with blind bolts
CTC04 [75]	Bonded sleeve splice joint
CTC05 [23]	Column-to-column connecting plate and access holes
CTC06 [76]	Extended column-to-column connection plate
CTC07 [77]	Column-to-column joint plate
CTC08 [78]	Overlaying extended endplates
CTC09 [79]	Column-to-column intermediate plates and interior bolts
CTC10 [80]	Column-to-column cruciform plate
CTC11 [81]	Interlocking pins, endplates and intermediate plate
CTC12 [82]	Endplates, intermediate plate and two resilient layers
CTC13 [83]	In-build hollow tenon component and side-plates
CTC14 [84]	Endplates, access hole and shape-memory alloy (SMA) bolts
CTC15 [85]	Endplates with guiding tenons and internal steel pipes
CTC16 [86]	Top and bottom tie assemblies with interconnect tube and nut

While some of these systems provide vertical and horizontal connectivity independently of each other through separate tie and endplates (**CTC01-04, CTC14, CTC16**), more advanced systems provide vertical and horizontal load transfer simultaneously by means of an intermediate plate between the columns' endplates (**CTC05-12, CTC15**), which enhances the shear stiffness of the module-to-module joint. In some of these connections, the main drawback is the presence of access holes in corner posts, favouring stress concentrations in critical regions and affecting the stress flow in the internal frame.

Trying to mitigate reduced access for fastening without introducing weak regions in the columns' sections, Cho et al. [74] investigated the use of blind bolts in the access-hindering portion of an external side-plate IMC (**CTC03**). However, the large number of bolts per node require laborious onsite fastening, unjustified for the relatively limited structural capacity delivered. A different approach was taken by Deng et al. [80], who mitigated the weakened column regions by welding cover plates after joining the columns of modules by means of an intermediate cross-shaped gusset plate (**CTC10**). Despite the beneficial effect of the additional steel plates, inspection operations of the internal bolted connection are severely obstructed.

Gunawardena [78] reduced the number of connection components by pre-attaching extended endplates with overlaying matching profiles (**CTC08**). However, the overlapping parts require a strict, sequential disassembly process, which hinders the potential for architectural flexibility in the scenario of intermediate module removal. Another attempt to optimise installation workflows was reported in the work of Wang et al. [79], who proposed a bolted endplate joint located inside the SHS posts (**CTC09**), tightened with a long twisting tool from the top of the module, similar to the tool required by **LD06** connection [54]. The weakness of this connection was in its large number of unique components and tedious welding tasks for pre-attaching the parts. Lacey et al. [81] introduced an adaptable connection which combined bolt-and-plate joints with the interlocking action of pins (**CTC11**). While the pre-welded locating pins improve site-installation of units, significant slippage is inflicted upon the joint due to the manufacturing tolerances in the bolt and pin holes.

While most authors have directed their attention towards constructional issues of IMCs, a few have improved the structural performance of these connections by exploring seismic mitigation strategies. Sultana and Youssef [84] investigated passive damage control systems by replacing the high-strength steel bolts in a column splice (**CTC14**) with superelastic shape-memory alloy (SMA) bolts and reported reduced residual drifts and good re-centring ability of braced modular frames as long as SMA connections were used at particular locations and the superelastic strain limit of SMA bolts was not exceeded. Sendanayake et al. [82] proposed two configurations which separated the endplates of columns from the intermediate steel plate (**CTC12**): one with washers and another with two layers of deformable, resilient material (rubber). While average, in terms of assembly/disassembly opportunities, the added rubber layers were efficient in dissipating energy and shifting the damage away from critical column sections.

A different approach was taken by Ma et al. [83], who proposed a joint in which columns are connected to an in-build component inserted inside the SHS profiles (**CTC13**). The design shows flexibility as it is configurable for any of the three types of IMCs (corner, external, internal). Connection is done horizontally from the sides, and the framing members are strengthened in the joint region by means of additional end and side plates.

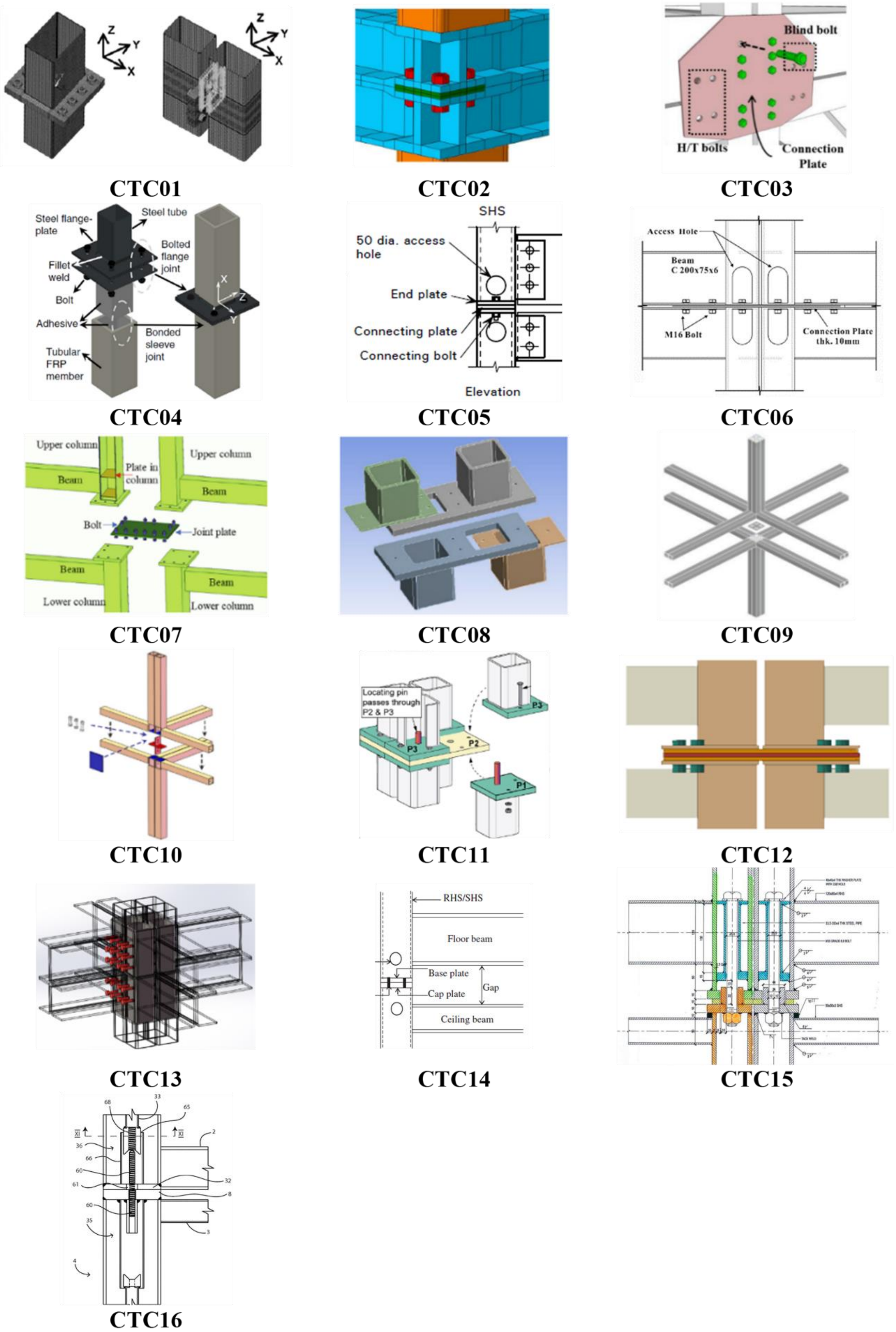


Fig. 9. Column-to-column bolted IMCs: CTC01 [72], CTC02 [73], CTC03 [74], CTC04 [75], CTC05 [23], CTC06 [76], CTC07 [77], CTC08 [78], CTC09 [79], CTC10 [80], CTC11 [81], CTC12 [82], CTC13 [83], CTC14 [84], CTC15 [85], CTC16 [86].

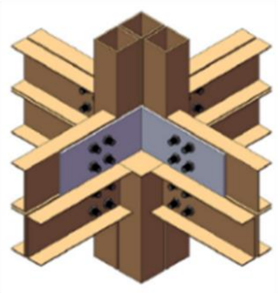
Error! Reference source not found.. **Studies on column-to-column bolted IMCs**

Index	Experimental		Numerical			Analytical
			Detailed			
	Small-scale	Meso-scale	Small-scale	Meso-scale	Simplified joint model	
CTC01	N/A	N/A	3D Solid (SOLID45); Ansys; Tensile/Shear/ Bending; [72]	N/A	Link elements; SAP2000; Six-storey 3D frame; Horizontal Equivalent Static Force; Response-Spectrum Analysis; Time History Analysis; [87] Connector elements; Abaqus; Five-storey 2D frame; Eigenvalue Buckling Analysis; [88]	Mechanical model; Formulae for effective length factor of columns; [88]
CTC02	N/A	N/A	N/A	3D Solid (C3D8I); Abaqus; One-storey one/two-sided 3D frame; [73]	N/A	N/A
CTC03	N/A	One-storey two-sided 2D frame; Cyclic lateral load; [74]	N/A	N/A	Frame elements; Midas-Gen; One-storey two-sided 2D frame; Monotonic lateral load; [74]	Mechanical model; [74]
CTC04	N/A	Four-point bending frame setup; [75]	N/A	3D Solid (SOLID185); Ansys Four-point bending frame setup; [75]	N/A	N/A
CTC05	N/A	N/A	3D Solid (C3D8R); Abaqus; Tension/Compression/Bending; [89]	3D Solid (C3D8R); Abaqus; One-storey two-sided 2D frame; Monotonic lateral load; [89]	Connector elements; Abaqus; One-storey two-sided 2D frame; Monotonic lateral load; [89]	N/A
CTC06	N/A	N/A	N/A	3D Solid; Abaqus One-storey two-sided 2D frame; Cyclic lateral load; [76]	Link elements; RUAUMOKO 2D; 3/5-storey 2D frame; Pushover Analysis; [76]	Mechanical model; [76]
CTC07	Bending; [77]	N/A	N/A	N/A	Spring elements; Ansys; 14-storey 3D frame; Time History Analysis; [77]	N/A
CTC08	Shear; [78]	N/A	3D Solid; Ansys; Shear; [78] 3D Solid (C3D8R); Abaqus; Shear; [82]	N/A	Link elements; RUAUMOKO 3D, SAP2000; 10-storey 3D frame; Time History Analysis; [78]	N/A
CTC09	N/A	One-storey two-sided 2D frame; Monotonic vertical load; [79]	N/A	N/A	N/A	N/A
CTC10	N/A	One-storey one/two-sided 2D frame; Monotonic/Cyclic vertical load; [80,90]	N/A	3D Solid (C3D8R); Abaqus One-storey one-sided 2D frame; Cyclic vertical load; [91]	N/A	Mechanical model; [90]
CTC11	Shear; [81]	N/A	3D Solid (C3D8R); Abaqus; Shear; [81]	N/A	Link elements; SAP2000; Six-storey 3D frame; Horizontal Equivalent Static Force; Response-Spectrum Analysis; Time History Analysis; [68]	Mechanical model; Connection design formulae; [92]
CTC12	Monotonic / Cyclic Bending; [82,93]	N/A	3D solid (C3D8R/H); Abaqus Bending; [82,93]	3D shell (S4R) and Timoshenko beam (B31); Abaqus 8-storey 2D frame; Time history analysis; [94]	N/A	N/A
CTC13	N/A	One-storey one-sided 2D frame; Monotonic vertical load; [83]	N/A	3D solid (C3D8R); Abaqus; One-storey one-sided 2D frame; Monotonic vertical load; [83,96]	Beam/Spring elements; Abaqus; One-storey one-sided 2D frame; Monotonic vertical load; [96]	Design formulae for connection components; [96]

		One-storey one-sided 2D frame; Monotonic lateral load; [95]		3D solid (C3D8R); Abaqus; One-storey one-sided 2D frame; Monotonic lateral load; [95]		
CTC14	N/A	N/A	N/A	N/A	Truss and Link elements; SeismoStruct; Six-storey 2D frame; Incremental Dynamic Analysis; [84]	N/A
CTC15	N/A	N/A	N/A	N/A	N/A	N/A
CTC16	N/A	N/A	N/A	N/A	N/A	N/A

2.3.2. Beam-to-beam (BTB) connections

Beam-to-beam joints are another common type of bolted IMCs, relocating the joint from the columns of the module between floor and ceiling beams (Table 5). The common elements employed in this type of connection are gusset plates of various geometries, engineered to closely fill the gaps between modules, optimising the unusable space between each of the floor and ceiling cassettes (



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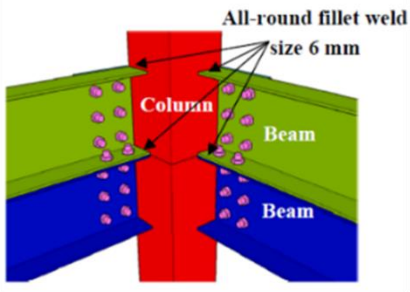

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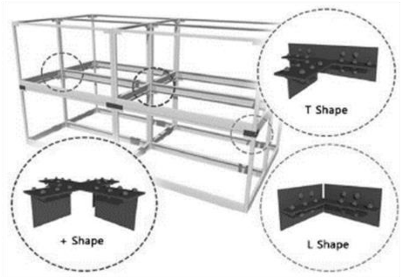
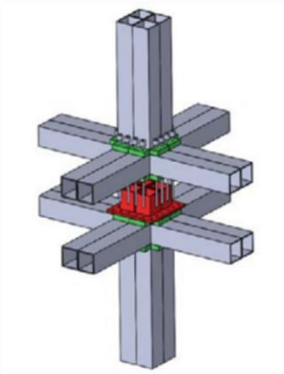
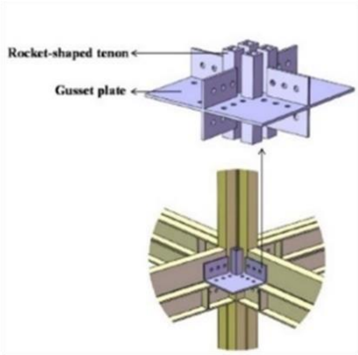


BTB03



BTB04



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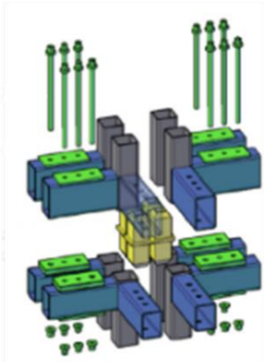

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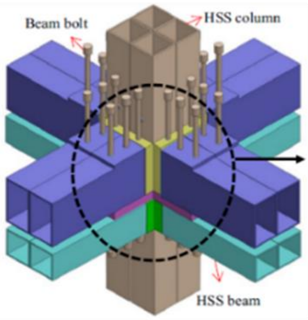

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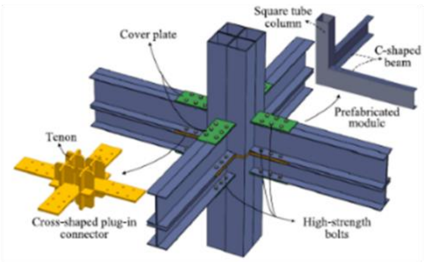

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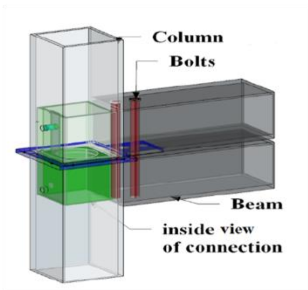

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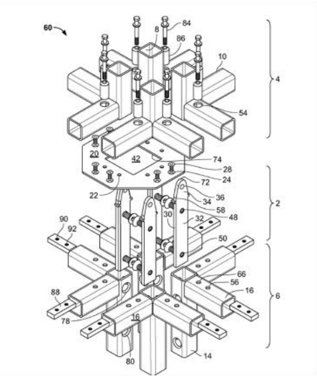

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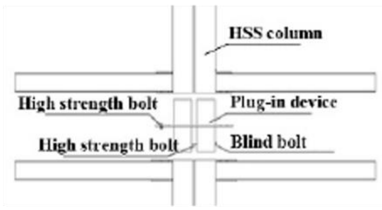

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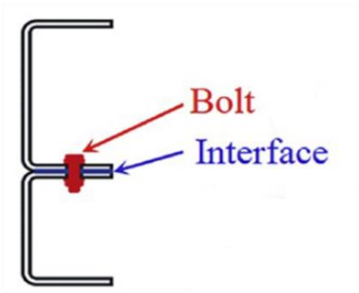


BTB12

Fig. 10).

Table 5. Beam-to-beam bolted IMCs

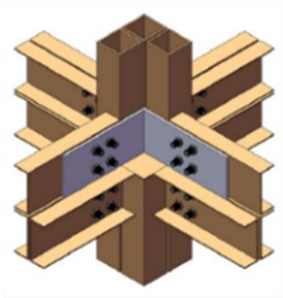
ID Code	Joint typology
BTB01 [97]	Web-to-web cruciform plate
BTB02 [98]	Web-to-web and flange-to-flange connector plates
BTB03 [99]	Beam-to-beam connection steel plates
BTB04 [34]	Bolted intermediate tenon plate
BTB05 [100]	Web-to-web cruciform socket-shaped tenon
BTB06 [101]	Beam-to-beam connection with plug-in tenon device
BTB07 [102]	Beam-to-beam interpenetrating tenon devices
BTB08 [103]	Beam-to-beam cross-shaped plug-in connector
BTB09 [61]	Tenon-shaped plug-in adapter with spring pins and bolted beams
BTB10 [104]	Bolted vertical steel plates, gusset plate and bolted beams
BTB11 [105]	Plug-in tenon device with high-strength and blind bolts
BTB12 [106]	Bolted PFC double beam with interface interaction

Park et al. [97] proposed a configuration capable of engaging eight units by bolting the webs of beams to a cross-shaped plate installed at the interface between modules (**BTB01**). However, the functionality of this system is limited to modular framings with parallel flange channel (PFC) beams. Similarly, the connection studied by Lyu et al. [98] benefits from the extra stiffness provided by a set of bolts on the flanges of C-beams (**BTB02**), while the cross-shaped plate is split up into separate cover plates, slowing down installation time. In similar fashion, Lee et al. [99] stiffened the beam-to-beam joint by adding a ceiling bracket and stiffener plates at ends of beams (**BTB03**). Even though the versatile geometries of these gusset plates promote a flexible IMC and facilitate easy access for fastening, the functionality remains limited to PFC profiles.

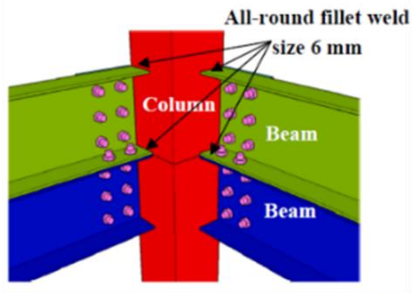
Tenons are commonly adopted in several beam-to-beam bolted IMCs (**BTB04-11**) and engineered to assist in guiding and alignment of modules during installation. Deng et al. [100] introduced a cruciform three-dimensional gusset plate with pre-welded socket-shaped tenons (**BTB05**). The additional bolts on the flanges of C-beams enhance the stiffness of the joint, while the long tenons reduce the buckling lengths of the SHS columns.

Several similar cast plug-in connectors with hollow box-shaped tenons were developed and proposed in the literature. While Pang et al. [34] (**BTB04**), Khan and Yan [102] (**BTB07**) and Bowron [104] (**BTB10**) introduced configurations where long bolts pass through the horizontal plates of the plug-in devices, interconnecting all parts of the joint together, the joint studied by Chen et al. [101] (**BTB06**) adopts a looser design with separate intermediate and cover plates. Additional horizontal blind bolts fixing the tubular columns to the plug-in tenons were added by Li [105] (**BTB11**), while

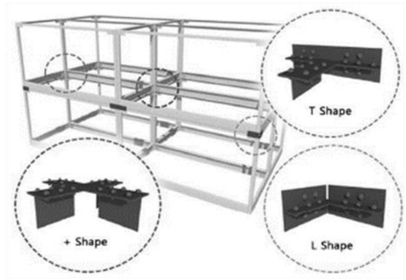
Nadeem et al. [61] introduced spring-activated pins on the tenons of the plug-in connector (**BTB09**), making the connection self-locking to some extent, as the joint still requires vertical high-strength bolts to properly connect the upper and lower modules. The IMC examined by Zhang et al. [103] (**BTB08**) can be regarded as a combination of **BTB05** and **BTB06**, with cross-shaped tenons in the plug-in connector and separate top and bottom cover plates fixing the channel beams of modules together. Besides limited access for engagement and intensive bolt fastening required by this type of joints, the main disadvantage resides in the difficulties posed by deconstruction due to the interconnectivity of numerous connection parts. Once assembled, the tenons of plug-in connectors make it difficult to disengage individual modules. In Xu et al.'s [106] connection (**BTB12**) the gap between floor and ceiling beams is eliminated, as modules are connected by bolting the beams along their length, benefiting from the combined double-beam action.



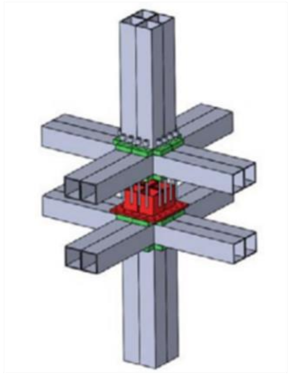
BTB01



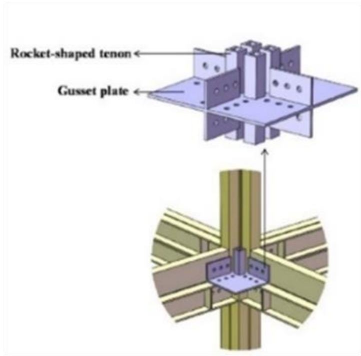
BTB02



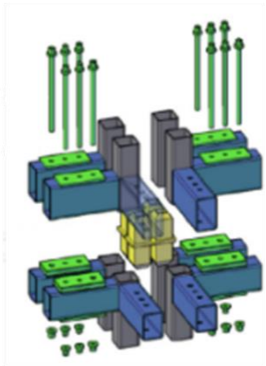
BTB03



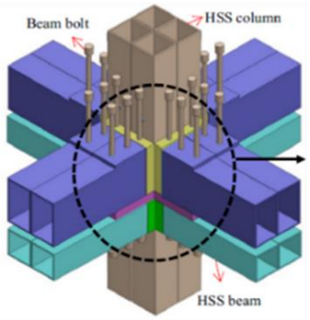
BTB04



BTB05



BTB06



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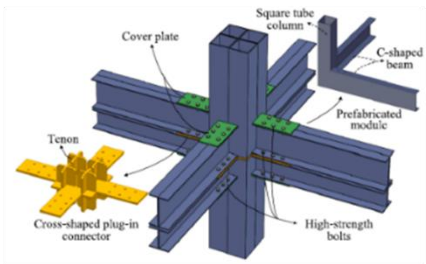
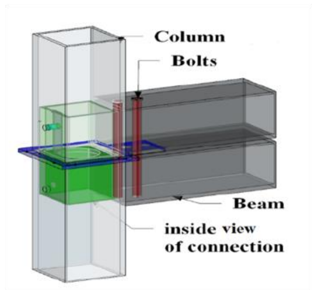


BTB08



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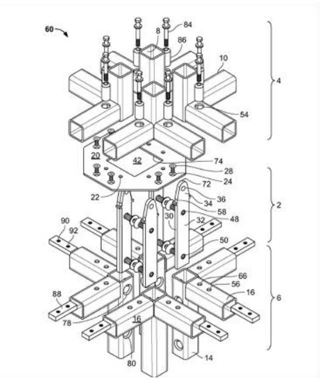
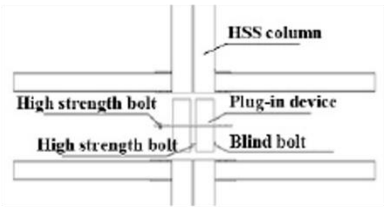
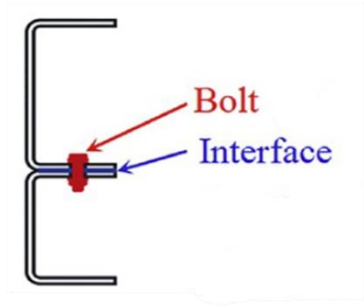


BTB10



BTB11



BTB12

Fig. 10. Beam-to-beam bolted IMCs: BTB01 [97], BTB02 [98], BTB03 [99], BTB04 [34], BTB05 [100], BTB06 [101], BTB07 [102], BTB08 [103], BTB09 [61], BTB10 [104], BTB11 [105], BTB12 [106].

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Index	Experimental		Numerical			Analytical
			Detailed		Simplified joint model	
	Small-scale	Meso-scale	Small-scale	Meso-scale		
BTB01	N/A	N/A	N/A	N/A	N/A	N/A
BTB02	Bending; [107]	Two-storey one-sided 3D frame; Monotonic vertical load; [98]	Bending; [107]	3D Solid (C3D8R); Abaqus Quarter of two-level one-sided 3D frame; Monotonic vertical load; [98]	Connector elements; Abaqus; Two-storey 2D frame; Eigenvalue Buckling Analysis; [108]	Mechanical model; [108]
BTB03	N/A	One-storey one sided 2D frame; Cyclic vertical load; [99,109]	N/A	3D Solid (SOLID45); Ansys; One-storey one sided 2D frame; Cyclic vertical load; [99,109]	N/A	N/A
BTB04	N/A	N/A	N/A	N/A	N/A	N/A
BTB05	N/A	N/A	N/A	N/A	N/A	N/A
BTB06	Compact tension test for material fracture toughness; [110]	One-storey one/two-sided 2D frame; Monotonic/Cyclic lateral load; [101,111]	3D Solid (C3D8R); Abaqus; Compact tension test for material fracture toughness; [110]	3D Solid (SOLID95); Ansys; One-storey one/two-sided 2D frame; Monotonic/Cyclic lateral load; [101,111] 3D shell (S4R) and 3D Solid (C3D8R); Abaqus One-storey two-sided 2D frame; Monotonic/Cyclic lateral load; [110] 3D Solid (C3D8R); Abaqus One-storey one-sided 2D frame; Monotonic lateral load; [102] 3D Solid (C3D8R); Abaqus One-storey one-sided 2D frame; Cyclic vertical load; [91]	Connector elements; Abaqus 4-storey 2D frame; Modal Analysis; Pushover Analysis [112]	N/A
BTB07	N/A	N/A	N/A	3D Solid (C3D8R); Abaqus One-storey one/two-sided 2D frame; Monotonic/Cyclic lateral load; [102]	Connector elements; Abaqus One-storey one/two-sided 2D frame; Monotonic lateral load; [102]	N/A
BTB08	N/A	N/A	N/A	3D shell (S4R), 3D Solid (C3D8R) and connector elements; Abaqus One-storey two-sided 2D frame; Cyclic lateral load; [103,113]	N/A	Mechanical model; [113]
BTB09	N/A	N/A	3D Solid (C3D20R); Abaqus Tension; [61]	3D Solid (C3D8R/C3D20R); Abaqus; One-storey one-sided 2D frame; Monotonic vertical load; [61]	N/A	N/A
BTB10	N/A	N/A	N/A	N/A	N/A	N/A
BTB11	N/A	N/A	N/A	N/A	N/A	N/A
BTB12	Bending; [106]	One-storey one-sided 2D frame; Monotonic lateral load; [95]	3D Solid (C3D8R; Abaqus Bending; [106]	3D Solid (C3D8R); Abaqus One-storey one-sided 2D frame; Monotonic lateral load; [95]	Tie interface; Abaqus 12-storey 3D frame; ULS and SLS evaluation under design wind actions [114]	Connection design formulae; [106] Mechanical model; Design formulae for equivalent bending stiffness, initial lateral stiffness; [95]

2.3.3. Fitting-to-fitting (FTF) connections

The third type of bolted IMCs stems from the common feature of engaging modules through corner fittings (Table 6). The shape of these cast corners ranges from the classic ISO design adopted from shipping containers to more refined and computationally optimised topologies (Fig. 11).

Table 6. Fitting-to-fitting bolted IMCs

ID Code	Description of joint configuration
FTF01 [115]	Steel hollow cube bracket
FTF02 [116]	Corner fitting and intermediate plate
FTF03 [117]	Corner fittings with gusset plates and locating pins
FTF04 [118]	Corner fittings with tie plates and spigots
FTF05 [119]	Corner fittings with tie plates and twist locks
FTF06 [120]	Intermediate rubber isolator, tenon plates and cover plates
FTF07 [121]	Corner fittings with transverse clamp
FTF08 [121]	Corner fittings with cross-shaped clamp
FTF09 [121]	Corner fittings with X-shaped clamp
FTF10 [121]	Bolted corner fittings
FTF11 [122]	Bolted square steel pipe blocks with internal circular pipes
FTF12 [123]	Corner fittings inserted through hollow steel beams, gusset plates and locating pins
FTF13 [66]	Vertically and horizontally bolted corner fittings vertical
FTF14 [124]	Corner fittings with vertical bolts through columns
FTF15 [125]	Corner fittings with internal threaded aperture
FTF16 [126]	Corner fittings with rubber isolation
FTF17 [127]	Corner fittings bolted to endplates and intermediate plates
FTF18 [128]	Corner fittings with external bolts and positioning plate
FTF19 [91]	Corner fittings with cruciform plate and horizontal bolts

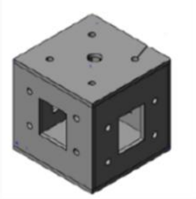
The IMC studied by Doh et al. [115] ties modular units horizontally and vertically by means of cubic steel boxes (**FTF01**), integrated into the structural frame of the building block. The concept introduces a practical and flexible assembly, accommodating different structural elements into the connection, yet with limited structural performance.

Suitable for container-like modules, the connection detail presented by Yu and Chen [116] joins typical ISO corner fittings by means of an intermediate plate and a single bolt (**FTF02**). The functional and manufacturing convenience come at the cost of limited structural performance, having been used in a building no taller than 5-storey MBS. A reworking of this configuration was used in a paper by Shi et al. [119], extending the cast corner to include spigots on the intermediate plate and moving the bolts from the corner towards the span of the floor beam (**FTF05**). Similarly, Shan et al. [118] studied a configuration which includes two bolts in each of the corner enclosures (**FTF04**). Others have developed corner fittings of different geometries, in which the bolts are passed through the hollow column sections and modules are fastened together by means of intermediate gusset plates (**FTF14, FTF15**) [124,125]. Chen et al.'s joint (**FTF17**) [127] was developed to connect modular slab-column steel assemblies by fastening the endplates of columns to intermediate corner fittings. While the configuration was not intended for volumetric off-site modular structures, it can be easily adapted to be used in this type of structural system as well. In Hu et al.'s joint (**FTF18**) [128], the corner fittings are extended and open-sided to allow access for fastening the bolts. Lian et al. [91] introduced a cruciform gusset plate between the corner fittings, with the vertical flange extended such that horizontal bolts connected adjacent modules (**FTF19**).

Seeking to improve the seismic resilience of IMCs, Wu et al. [120] studied a plug-in device which includes a lead rubber bearing (LRB) between two intermediate plates with locating spigots (**FTF06**). The joint holds the beams of adjacent modules together by using bolted steel clamps, displaying a disassembly and reuse friendly design. Similarly, corner fittings of vertically stacked modules can be bolted together by means of an intermediate steel-rubber isolator with extended endplates as showcased in joint **FTF16** [126].

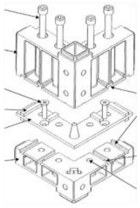
Feng et al. [121] focused on four different joint configurations for typical container corner fittings (**FTF07-10**), each adapted for a specific location within the anatomy of a fully modular building system. Three of the connections make use of clamps (transverse, cross-shaped and X-shaped) which make them compliant with DfA and DfD principles, while the fourth one connects the corners of modules by means of high-strength bolts. Moreover, these designs demonstrate flexibility and efficiency as the mechanical properties of these joints are tailored for their specific applications. Epaminondas' [66] design (**FTF13**) envisages an external IMC, connecting the corner fittings of modules both by horizontal and vertical bolts.

The IMC developed by Z-Modular [117] is called Vectorbloc and incorporates both "intra-" and "inter-" connection details, enabling the assembly of volumetric modular units made of hollow sections, welded to optimised block connectors (**FTF03**). Horizontal connection between adjacent modules is achieved through a gusset plate (adaptable for corner, external and internal joints alike) which ties lower-level modules using flat head cap screws (FHCP). A registration pin welded to the plate enhances constructability, while vertical connection between the fittings is secured by two high-strength socket head cap screws (SHCP). Similar configurations were also proposed by Lee et al. [122] (**FTF11**) and Bowron et al. [123] (**FTF12**), who also developed innovative corner fittings which house long vertical screws fixing upper and lower modules together. In joint **FTF11** the inner threaded holes are replaced by shop-welded nut caps which tighten the screw connection, while in joint **FTF12**, the extended sides of the corner fitting are inserted in the hollow beam sections and the vertical screws clamp all components together.

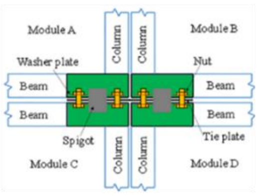


FTF01

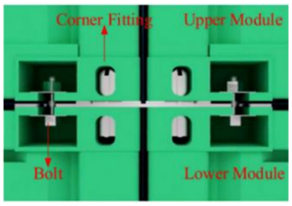
FTF02



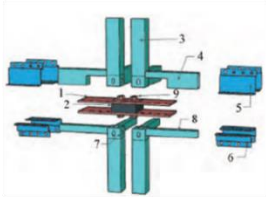
FTF03



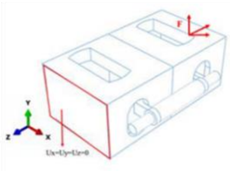
FTF04



FTF05

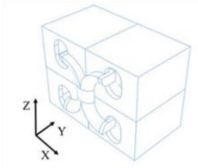


FTF06

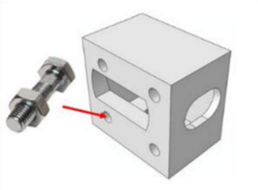


FTF07

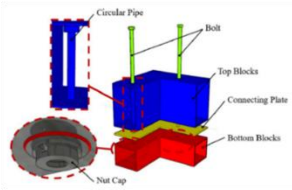
FTF08



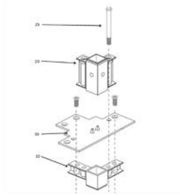
FTF09



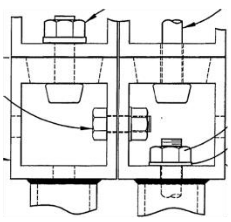
FTF10



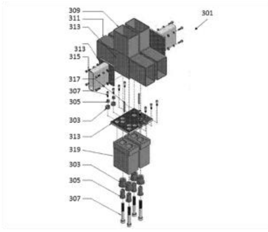
FTF11



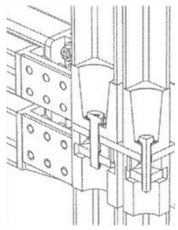
FTF12



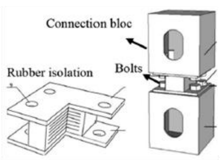
FTF13



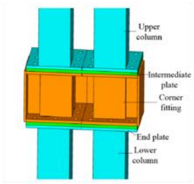
FTF14



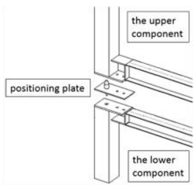
FTF15



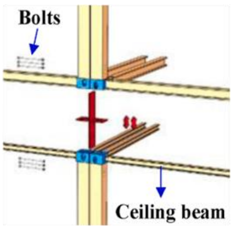
FTF16



FTF17



FTF18



FTF19

Fig. 11. Fitting-to-fitting bolted IMCs: FTF01 [115], FTF02 [116], FTF03 [117], FTF04 [118], FTF05 [119], FTF06 [120], FTF07 [121], FTF08 [121], FTF09 [121], FTF10 [121], FTF11 [122], FTF12 [123], FTF13 [66], FTF14 [124], FTF15 [125], FTF16 [126], FTF17 [127], FTF18 [128], FTF19 [91].

Error! Reference source not found.. **Studies on fitting-to-fitting bolted IMCs**

Index	Experimental		Numerical			Analytical
			Detailed		Simplified joint model	
	Small-scale	Meso-scale	Small-scale	Meso-scale		
FTF01	Shear/ Bending; [115]	N/A	2D plate (Quad 4) and 3D Brick (Hexa 8); Strand7 Shear/Bending; [115] 3D Solid (C3D8R); Abaqus Shear; [42]	N/A	N/A	N/A
FTF02	N/A	N/A	N/A	N/A	Beam elements; Midas; 5-storey 3D frame; Response-Spectrum Analysis; [116]	N/A
FTF03	Tension/Compression; [129]	One-storey one-sided 3D frame; Monotonic vertical load; [130]	3D Solid (C3D10 and C3D20R); Abaqus; Tension/Compression; [129]	3D Solid (C3D10 and C3D20R); Abaqus; One-storey one-sided 3D frame; Monotonic vertical load; [130]	N/A	N/A
FTF04	N/A	N/A	3D Solid; Abaqus; Tension/Shear; [118]	N/A	Link elements; ETABS; 25-storey 3D frame; Response-Spectrum Analysis; Time History Analysis; [118]	N/A
FTF05	N/A	N/A	N/A	N/A	Connector elements; Abaqus; 20-storey 3D frame; Response-Spectrum Analysis; Time History Analysis; [119]	N/A
FTF06	N/A	N/A	N/A	N/A	N/A	N/A
FTF07	N/A	N/A	3D Solid (C3D8R); Abaqus; Tension/Shear; [121]	N/A	Spring elements; Abaqus; 4-storey 3D frame; Modal Analysis; Response-Spectrum Analysis; Time History Analysis; [121]	N/A
FTF08	N/A	N/A	3D Solid (C3D8R); Abaqus; Tension/Shear; [121]	N/A	Spring elements; Abaqus; 4-storey 3D frame; Modal Analysis; Response-Spectrum Analysis; Time History Analysis; [121]	N/A
FTF09	N/A	N/A	3D Solid (C3D8R); Abaqus; Tension/Shear; [121]	N/A	Spring elements; Abaqus; 4-storey 3D frame; Modal Analysis; Response-Spectrum Analysis; Time History Analysis; [121]	N/A
FTF10	N/A	N/A	3D Solid (C3D8R); Abaqus; Tension/Shear; [121]	N/A	Spring elements; Abaqus; 4-storey 3D frame; Modal Analysis; Response-Spectrum Analysis;	N/A

					Time History Analysis; [121]	
FTF11	N/A	One-storey one-sided 2D frame; Monotonic vertical load; [122]	N/A	3D Solid (C3D8R); Abaqus; One-storey one-sided 2D frame; Monotonic vertical load; [122]	N/A	N/A
FTF12	N/A	N/A	N/A	N/A	N/A	N/A
FTF13	N/A	N/A	N/A	N/A	N/A	N/A
FTF14	Shear; [131,132]	One-storey one/two-sided 2D frame; Cyclic lateral load; [131,132]	3D Brick; Strand7; Bending; [131,132]	N/A	29-storey 3D frame; Performance Based Design; Nonlinear Response History; [131,132]	N/A
FTF15	N/A	N/A	N/A	N/A	N/A	N/A
FTF16	N/A	N/A	N/A	N/A	N/A	N/A
FTF17	N/A	N/A	N/A	N/A	Beam elements; Midas; 3-storey 3D frame; Linear Elastic Analysis; [127]	N/A
FTF18	Bending; [128]	N/A	3D Solid (C3D8I); Abaqus; Bending; [128]	N/A	N/A	N/A
FTF19	N/A	N/A	N/A	3D Solid (C3D8R) and spring connectors; Abaqus; One-storey one-sided 2D frame; Cyclic vertical load; [91]	N/A	N/A

Having completed the classification of IMCs, an inclusive and comprehensive record has been produced, revealing the multitude of existing connection systems and thus, displaying the magnitude of the topic discussed herein. In the following sections, the assigned abbreviations will be used when referring to a particular connection system to ensure clarity and consistency throughout the discussion, critical review and ranking of the inter-module joints.

3. Multi-attribute ranking of IMCs

3.1. The framework of the proposed scoring system

As discussed in the introduction, a new scoring system (Table 7) has been developed in this study to highlight opportunities and challenges in existing connection systems, helping the development of future designs as well as identifying potential areas for improvement in existing ones. In lack of consistent quantitative data about the designs considered, a qualitative approach based on visual inspection combined with engineering knowledge and intuition was adopted in the characterisation of the connection systems. To this end, it must be noted that the rankings presented in the following section are a subjective product of the authors' understanding and level of knowledge and that other interpretations may lead to somewhat different results. For this reason, all weightings have been kept equal to ensure an overall level of impartiality. Nevertheless, it is believed that through the scoring metrics proposed herein a practical, comprehensive, and scalable multi-attribute ranking system is achieved, which can essentially be used as is or tailored by other researchers and practising engineers for their own objectives.

Table 7. Description of the proposed scoring system

A. Structural performance metrics		
Metric	Score	Description
VH	0	Does not meet the requirement
	1	Meets the requirement
DR	1	Low energy dissipating capability, no self-centring
	2	Moderate energy dissipating capability, moderate or no self-centring
	3	Good energy dissipating capability, self-centring
FD	1	Limited scaling opportunities
	2	Moderate scaling opportunities
	3	Good scaling opportunities
B. Constructional performance metrics		
Metric	Score	Description
DfA	1	Complex: no self-aligning/self-locating features, large number of tasks, difficult access, complex tooling
	2	Moderate: self-aligning/self-locating features, moderate number of tasks, moderate access, moderate tooling

	3	Lean: efficient self-aligning/self-locating features, small number of tasks, easy access, simple tooling
DfD	1	Difficult to disassemble
	2	Easy to disassemble and parts of the assembly need to be replaced
	3	Easy to disassemble and parts of the assembly can be reused
TC	1	Limited tolerance control
	2	Moderate tolerance control
	3	Good tolerance control
C. Manufacturing performance metrics		
Metric	Score	Description
JC	1	Large number of parts; complex geometry; complex manufacturing sequences; difficult to mass-produce;
	2	Moderate number of parts; reasonable geometry; moderate manufacturing sequences; reasonable to mass-produce
	3	Small number of parts; Easy-to-manufacture geometry; easy to mass-produce;
EI	1	Difficult integration of connection parts into final joint (e.g., welding of complex parts)
	2	Reasonable integration of connection parts into final joint (e.g., fastening)
	3	Simple joint configuration (e.g., no post-manufacturing integration required or fast procedures such as inter-locking)
EP	1	Demanding pre-attachment process (e.g., welding of additional components to finished modules)
	2	Reasonable pre-attachment process (e.g., fastening of additional components to finished modules, drilling holes)
	3	Easy pre-attachment process (e.g., no additional components required, or connection parts are already integrated into module framing i.e., corner fittings)

Notes: VH - Vertical and horizontal connectivity; DR – Design resilience; DF – Design flexibility; DfA – Design for Assembly; DfD – Design for Disassembly; TC – Tolerance control; JC – Joint complexity; EI – Ease of integration; EP – Ease of pre-assmbly

Scoring for all attributes was done on 3-point rating scales, except for the VH structural attribute which considers a 0-1 integer scale corresponding to whether a connection meets or does not meet the requirements. The maximum possible score for a system is 25 points, while the minimum a connection can score is 8. A detailed breakdown of the scales and scoring for each metric is presented in the following sections.

3.2. Structural metrics

The structural metrics used in the proposed scoring system include three performance indicators, namely reliable vertical and horizontal connectivity (VH), design resilience (DR) and design flexibility (DF).

3.2.1. Vertical and horizontal connectivity (VH)

This attribute evaluates connections based on their ability to provide reliable load paths to resist both vertical tension due to uplift of module (effect caused by strong lateral loading on high-rise MBSs) and vertical and horizontal shearing due to relative displacement between modules (effect caused by the discrete arrangement of IMCs in steel MBSs with corner-supported volumetrics).

3.2.2. Design resilience (DR)

For many years, the most widely adopted design paradigm for structures located in earthquake zones has been that of seismic resistance, provided either by strength (structural systems designed to always remain in the elastic strain state) or ductility (structural systems designed to dissipate energy through inelastic deformation suffered by its members). Out of the two, the latter is the most popular choice, being a cost-effective solution for most building structures. It's main principle is to avoid brittle failure by ensuring the formation of adequate plastic-hinge mechanisms through adequate detailing, such that regions/components susceptible to nonlinear behaviour are capable of transferring forces and dissipating sufficient energy to mitigate the cyclic action of ground accelerations [133]. In steel moment-resisting frames (MRFs), joints are typically detailed to achieve rigid full-strength behaviour and thus steer the plastic regions towards the beams' ends [134] (also known as the "strong column – strong joint – weak beam" concept). Among the more refined systems developed based on this principle are the reduced beam section (RBS) (also known as "dogbone") connections [135–137], which keep the column and connection parts damage-free by localising the inelastic strains into weakened beam regions.

However, the main drawback of this approach is the occurrence of large residual drifts and permanent damage in structural framing members. From a code-related perspective, FEMA P-58-1 [138] introduced four damage classes (DS1-4), where DS1 requires a residual story drift less than 0.2% in order to avoid structural realignment, yet non-structural components would still require repair works. Using such performance-based criteria to assess a building's post-hazard condition is far from a trivial task, especially when it comes to elements with large inelastic strains, often determining retrofit assessors to recommend demolition straight away.

This issue has led to the emergence of the "structural fuse" elements, engineered to "take the hit" and dissipate seismic input energy, while the main structural elements remain in elastic strain state [139]. These can be either parts of the connection [140,141] (column flange, endplate, angle flange cleats, T-stubs) or standalone devices integrated in the connection assembly. Among these, some examples with good prospects of being integrated in connection configurations include slit dampers [142–147] or pins [148–152]. Usually, these fuse elements are engaged by developing some controlled rocking or sliding mechanisms into the joint and are designed to be easy to repair or even replace. However, large distortions may cumber the replacement of these systems. Hence, many researchers have focused on developing self-centring energy-dissipating (SCED) connections which aim to reduce residual drifts by structural-based approaches like post-tensioning [153–155], or material-based approaches which make use of elastomeric self-recovery [156–158] or shape-memory alloys' (SMA) superelasticity [159–163]. Out of the three, the commonness and reliability of elastomeric materials make them a safe and relatively economic option.

In this context, the design resilience (DR) metric assesses the ability of IMCs to mitigate or completely avoid permanent damage (Damage Avoidance Design or DAD) in the members of modular units that form the structural framing of MBSs. Therefore, high scores in this metric reflect that IMCs are capable of sustaining large elastic deformations without damaging the connecting members by concentrating the damage in structural fuses. Ideally the whole connection assembly also possesses self-centring abilities to reduce residual drifts and ease retrofitting.

3.2.3. Design flexibility (DF)

Flexibility in design is a crucial attribute to have in structural connections, especially when considering the applicability of particular connection systems to a wide range of building layouts and heights. In this sense, design flexibility translates into the opportunities of studied configurations to be adaptable for any of the three types of inter-module joints (corner, external or internal) or to be scalable in order to satisfy various loading magnitudes and/or conditions required by different design scenarios. This is usually done by mirroring parts of the configuration or by slightly changing geometric parameters of connecting parts. Thus, the design flexibility of IMCs was assessed based on the ease to adapt or scale their configurations for more than just one application.

3.3. Constructional metrics

The constructional metrics adopted in this appraisal are represented by three performance indicators: Design-for-Assembly (DfA), Design-for-Disassembly (DfD), Tolerance control (TC).

3.3.1. Design for Assembly (DfA)

In volumetric modular construction the main share of workload is done off-site, leaving only a few tasks to be done on-site, among which connecting the modules effectively has a great influence on the rate of raising a new modular structure. It is therefore crucial that IMCs present features which facilitate self-alignment (e.g., pins, tenons, spigots), self-guidance (plug-and-play modules) and are devised for practical and accessible joining operations that require low-to-moderate human intervention.

3.3.2. Design for Disassembly (DfD)

Design for Disassembly (or Deconstruction) is a concept that increases the feasibility to deconstruct and reuse buildings instead of demolishing them altogether. Along with other strategies such as Design for Adaptability and Design for Reuse, the main aim of DfD is to improve the end-of-life management of buildings by changing the paradigm from Cradle-to-Grave towards more environmentally-friendly strategies like Cradle-to-Cradle, thus maximising the life cycle of already-built structures [164].

Based on Guy and Ciarimboli [165], three of the ten key principles of DfD of buildings are related to structural connections and require them to be easily accessible and to avoid chemical joints which are difficult to dismantle or recycle in favour of standardised bolted connections with straightforward tooling requirements.

As rightfully stated by Pongiglione et al. [166], "steel structures already meet the principles of DfD but their potential for deconstruction can be significantly improved”. In this regard, practical steel connections which do not require fastening or unfastening bolts for installation or dismantling are the well-known ATLSS connections [167,168] and the Quicon system [169]. There are also many DfD-friendly bolted connections like the ConXL/XR connections [170], the Modular Housing System (MHS) connection [171], the innovative 3D plug-and-play connection [172–174] or clamp connections developed by Lindapter [175] or Pongiglione et al. [166] which avoid drilling in structural elements increasing their reuse prospects.

When it comes to steel MBSs, the compact and ready-made nature of their volumetrics create the prospect of dismantling the modular frame to either rebuild it at a different site or to reconfigure its existing layout. For this purpose, besides the structural aspects regarding residual stresses and the potential reuse of structural cassettes, another important attribute is that IMCs exhibit DfD-friendly designs that allow for fast and intuitive reverse engineering.

3.3.3. Tolerance control (TC)

Even in highly controlled environments like off-site manufacturing shops, fabrication errors can creep into the structure of modules in the form of incorrect dimensions, out-of-verticality or bowing of members. While in traditional steel frame construction such irregularities may be accommodated easier due to the flexibility offered by joinery of 1D elemental construction, stacking of modules introduces some difficulties when positioning modules on top of each other. IMCs play a crucial role in correcting the positional errors over the building height and for this purpose connection systems require a certain level of tolerance control. This metric assesses the extent to which IMCs can accommodate build-up of constructional tolerances (i.e., due to stacking of modules with geometric imperfections) without jeopardising the aesthetics and structural integrity of the MBS.

3.4. Manufacturing metrics

The IMCs herein were assessed by their capability of meeting the following three manufacturing performance indicators: joint complexity (JC), Ease of integration (EI) and Ease of pre-assembly (EP).

3.4.1. Joint complexity (JC)

Joint complexity (JC) assesses the level of detail and regularity of IMC configurations, the number of parts making up the connection assembly as well as prospects of being mass-produced, all being attributes which can severely impact the cost and time of manufacturing of IMCs.

3.4.2. Ease of integration (EI)

Ease of integration (EI) measures the complexity of in-shop fabrication processes required for delivering the final connection part by combining all individual parts into the complete IMC ready for installation.

3.4.3. Ease of pre-assembly (EP)

The ease of pre-assembly (EP) metric is used to determine whether finished joints can be attached to modules in-shop with ease in terms of complexity of required assembly procedures (e.g., welding, cutting, drilling, fastening).

Based on the considerations regarded above, the IMCs identified in the literature were reviewed and ranked in the next section.

4. Application of the proposed scoring system to assess the performance of IMCs

The multi-attribute rankings presented herein were used to determine the highest-scoring IMCs for each performance category, highlighting the key features which can be attributed to each system's success.

The detailed rationale behind the scoring method is discussed below for one representative connection system from each of the typologies presented in the classification from Section 2. The rest of the connections were assessed using similar judgements as those expressed below and the scores for each metric can be monitored in Table 8.

Table 8. Scores for the IMCs in the literature

ID	Structural Metrics			Constructional Metrics			Manufacturing Metrics			Total
	VH	DR	DF	DfA	DfD	TC	JC	EI	EP	
LD01	0	1	1	3	2	2	3	1	3	16
LD02	1	1	1	3	2	2	1	3	1	15
LD03	1	1	1	2	2	2	2	3	3	17
LD04	1	2	1	3	1	1	1	1	3	14
LD05	1	1	1	3	2	1	1	2	3	15
LD06	1	2	1	3	1	2	1	1	3	15
LD07	1	2	1	3	1	2	1	1	3	15
PT01	1	2	1	1	1	2	2	2	1	13
PT02	1	2	1	1	1	3	2	1	1	13
PT03	1	2	1	1	1	3	3	1	1	14
PT04	1	2	1	2	2	3	3	1	1	16
PT05	1	2	1	1	1	3	2	1	1	13
PT06	0	2	1	1	1	3	2	2	1	13
CTC01	0	2	2	2	2	1	2	3	1	15
CTC02	0	2	2	2	2	1	1	3	3	16
CTC03	0	2	2	1	1	1	3	3	3	16
CTC04	0	2	2	2	2	3	2	1	2	16
CTC05	1	2	1	2	2	1	3	3	1	16
CTC06	1	2	2	1	1	1	3	3	1	15
CTC07	1	2	2	1	1	1	3	3	2	16
CTC08	0	2	2	2	1	2	3	3	2	17
CTC09	1	2	1	2	2	1	1	3	1	14
CTC10	1	2	2	1	2	2	2	1	1	14
CTC11	1	2	2	2	2	3	2	3	2	19
CTC12	1	2	2	2	2	2	3	3	2	19
CTC13	1	2	2	1	1	2	3	1	3	16
CTC14	0	3	2	2	2	1	2	3	1	16
CTC15	1	2	1	1	1	2	3	2	1	14
CTC16	0	1	1	2	3	3	2	2	1	15
BTB01	1	2	2	1	1	2	3	3	3	18
BTB02	0	2	2	1	1	2	3	3	3	17
BTB03	1	2	2	1	1	2	3	2	3	17
BTB04	1	2	2	1	1	3	2	2	3	17
BTB05	1	2	2	1	1	3	2	1	3	16
BTB06	1	2	2	1	1	2	2	1	2	14
BTB07	1	2	2	1	1	3	1	1	2	14
BTB08	1	3	3	1	3	3	1	1	2	18
BTB09	1	2	3	3	2	3	2	1	3	20
BTB10	1	2	3	2	2	2	1	2	2	17
BTB11	1	2	2	2	2	3	2	1	1	16
BTB12	1	1	1	2	1	2	3	3	2	16
FTF01	1	2	2	1	1	2	3	1	3	16
FTF02	1	1	1	2	2	2	3	1	2	15
FTF03	1	2	3	2	2	3	1	3	3	20
FTF04	1	1	1	2	2	2	2	2	3	16
FTF05	1	1	1	2	2	2	2	2	3	16
FTF06	1	3	3	2	3	3	1	2	3	21
FTF07	1	1	1	2	2	2	1	3	3	16
FTF08	1	2	1	2	2	2	2	1	3	16
FTF09	1	2	1	2	2	2	2	3	3	18
FTF10	0	2	2	1	1	2	3	3	3	17
FTF11	1	2	3	2	2	3	2	3	3	21
FTF12	1	2	3	2	2	3	1	3	3	20
FTF13	1	1	1	2	2	2	3	3	3	18
FTF14	1	2	1	1	1	2	2	3	3	16
FTF15	1	1	1	1	1	2	2	3	3	15
FTF16	0	2	2	2	2	2	1	3	2	16
FTF17	1	2	2	2	2	2	2	1	2	16
FTF18	1	2	2	2	2	2	2	1	3	17
FTF19	1	2	2	2	2	2	3	3	3	20

For IMCs with locking devices, system **LD03** was assessed as follows. A VH score of 1 was considered as the system can transfer both vertical loads (through the tensile capacity of a rotating rod) and horizontal loads (through bending and shear of an intermediate steel plate). A DR score of

1 was given as the connection possesses no means of energy dissipation or self-centring. The DF score of 1 was attributed based on the limited prospects of scalability by only having the option to change some parameters for the rotating rod part. A DfA score of 2 was accorded for the convenience of installing and fastening a single bolt. The DfD score of 2 was attributed as the connection can be easily dismantled, yet the majority of its parts and framing elements cannot be reused after a damaging event. The TC score of 2 was based on the presence of corner fitting which can help accommodate large constructional tolerances. The JC score of 2 is attributed to the relatively small number of components required by the joint, yet not very common or standardised to fabricate. An EI score of 3 was awarded as the final connection system can easily be integrated by interlocking its components. An EP score of 3 was given for the joint's clever devices which only requires rotating the rod to pre-attach the connection to the corner fittings.

From post-tensioned IMCs, **PT04** was chosen for a detailed breakdown of its metric scores. The VH score of 1 was given as in the case of connection **LD04** because the joint can transfer both vertical and horizontal loads through the PT rod and an intermediate plate. A DR score of 2 was accorded because the system may be capable of dissipating seismic energy at the ends of beams and may display some PT-based re-centring, yet resilience is limited by the permanent damage. The low DF score of 1 was attributed to the lack of scalability due to the single-rod design. A DfA score of 2 was considered as the joint only requires fastening of one threaded rod, access is provided through an opening, the shear key can provide self-guidance during installation and difficulties of post-tensioning are partly mitigated by only requiring local post-tensioning. The easy-to-disassemble design with limited reuse prospects due to lack of resilience resulted in a medium DfD score of 2. The presence of the shear key as well as the plates welded inside the SHS columns can help accommodate constructional tolerance, thus a TC score of 3 was given. A JC score of 3 is considered as the joint incorporates a relatively small number of parts which are all common and easy to manufacture. However, the low EI and EP scores of 1 are an effect of the welding required to fabricate the shear tenon as well as the welding required to pre-attach the inner plates and cutting for the access openings.

The following observations are given in support of the scores for joint **CTC12**. The joint is capable of both vertical and horizontal load transfer, thus the VH score is 1. Even though the joint demonstrates very good energy dissipation provided by the resilient rubber layers which can concentrate damage in the endplates, it can be difficult to repair or replace the damaged parts, resulting in a DR score of 2. The connection was also given 2 points for DF as the typical bolted splice design is fairly customisable for a wide range of applications. The 2 points for DfA are based on the reduced number of tasks for installation and lack of any self-guiding features. The joint also scored 2 for DfD as the bolts are demountable, yet in the event of an earthquake the damaged endplates may hinder the disassembly operation. The simplicity of the endplate-to-endplate splice connection offers some leeway in terms of constructional tolerances, however the lack of geometric features which can control grid alignment like corner fittings leads to a TC score of 2. The high scores of 3 for manufacturing metrics like JC and EI are supported by the common and small number of parts, which require no additional integration tasks for delivering the final system. The 2 points for EP are attributed to the conveniency of only pre-attaching endplates to the columns ends, yet welding tasks prevent the maximum score.

The assessment of the **BTB08** connection is based on the following judgement. Vertical and horizontal load transfer is ensured by the bolts running through the cross-shaped plug-in connector, thus the VH score is 1. The maximum DR score of 3 is attributed to the self-centring disc spring haunch braces which effectively reduce the permanent damage and residual displacements of the assembly. The configuration of the bolted joint provides great flexibility in detailing the connection for all types of layouts or framing members, thus the DF score of 3. The connection can be tedious to assemble in internal joints due to the numerous bolts, thus the joint's DfA score is 1. On the other hand, the maximum DfD of 3 is ensured by the demountability of the bolts combined with the great potential for reuse provided by the self-centring energy dissipating devices. Constructional tolerances can be accommodated with the help of the bolted plug-in connector which facilitates module alignment, therefore a TC score of 3 was considered. The joint scored 1 point for both JC and EI metrics, as the joint is fairly complex with numerous separate parts which are not common to manufacture (i.e., the self-centring disc spring haunch braces) and integrate into final components. An EP score of 2 was awarded as no welding is required to pre-attach the plates and the SC haunch braces can be bolted to the modular framing.

The following aspects were considered when assessing the **FTF06** connection. A score of 1 was given for the ability to transfer both vertical and horizontal loads through the bolted plates of the lead-rubber bearing (LRB) part. Energy dissipation and damping is provided by the lead core of the LRB, and some self-recovery may be present due to the rubber's hyperelasticity, thus a DR score of 3 was considered. As the bolted clamps can be accommodated for any layouts or types of framing members, the joint scored 3 points in the DF metric. Access can easily be provided for fastening the clamps, yet a large number of bolts per joint are required, thus the DfA score of 2 was considered. In terms of DfD, the connection scored 3 points as the reduced plastic strains ensured by the LRB device combined with the bolted clamps which avoid drilling holes in the module members improve the reuse opportunities after the connection is dismantled. The TC metric also got 3 points as the decoupled design which introduced the gap between ceiling and floor beams combined with the spigots present in the plates of the LRB can help accommodate large constructional tolerances. A low score of 1 for the JC metric was attributed for the less common shapes of the steel clamps and the manufacturing of the LRB. The EI score of 2 is due to simple process of integrating the connection parts into the final joint as once the LRB connector is manufactured it only remains to attach it to the modules and fasten the clamps. Finally, the EP metric scored 3 points as the LRB connector and clamps can easily be pre-attached to modules by fastening a few bolts and corner fittings come as built-in parts of the modular frame.

At the end of the scoring stage, the total scores per each category were re-arranged in ascending order to plot the multi-attribute rankings per metric (Fig. 12-Fig. 14). These results revealed what the most promising IMCs are for each metric as well as which were the best-performing connections for each type of system. Afterwards the appraisal was completed by an overall ranking based on the total scores for each IMC (Fig. 15).

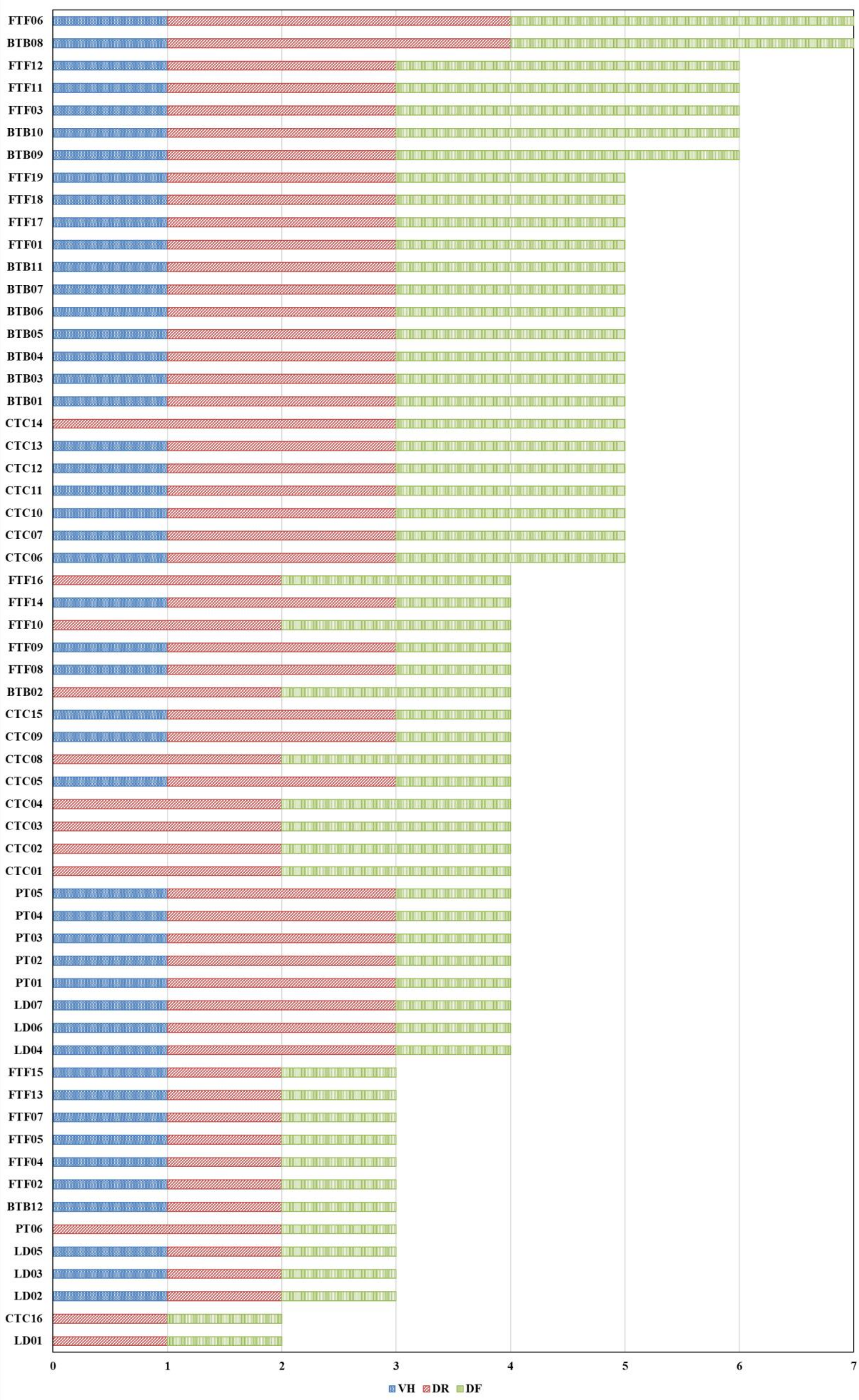
4.1.1. Ranking based on structural metrics

From the ranking based on structural metrics in Fig. 12, it becomes clear that the majority of existing IMCs can simultaneously transfer both vertical and horizontal loads, usually through the means of gussets or other similar intermediate plates which connect modules horizontally, while all IMCs are designed to at least transfer axial tensile or compressive forces.

The best scoring connections in the design resilience (DR) metric are those which are capable of dissipating energy without damaging the framing elements of modules and ideally provide some self-recovery. As the literature review showed, such feats have been achieved by integrating various components or damping devices (i.e., post-tensioned strands/rods, resilient rubber layers, lead-rubber bearings, self-centring haunch braces, shape-memory alloy bolts) into the assembly of the connection or structural framing of the modules.

In terms of design flexibility (DF), the best scoring connections were the ones with configurable designs which can be adapted to fit all types of joints (corner, external, internal), that do not depend on the type of modular framing elements, and which usually consist of bolted connections which can be easily scaled by modifying the number, layout, or diameter of bolts.

The best scoring connection systems in the structural metrics are **FTF06** and **BTB08**, for their high DR scores, owing to the self-centring energy dissipative system (i.e., the LRB and disc spring haunch braces) integrated in their configurations. These systems are followed closely by two beam-to-beam bolted joints (**BTB09** and **BTB10**) and three fitting-to-fitting bolted joints, namely the Vectorbloc connection (**FTF03**) and other similar variants (**FTF11**, **FTF12**), which are not as efficient in design resilience but compensate through their flexible configurations.


FTF06
BTB08
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BTB07
BTB06
BTB05
BTB04
BTB03
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FTF05
FTF04
FTF02
BTB12
PT06
LD05
LD03
LD02
CTC16
LD01
0
1
2
3
4
5
6
7
VH
DR
DF

Fig. 12. Ranking of IMCs based on structural metrics

4.1.2. Ranking based on constructional metrics

The ranking of IMCs based on constructional metrics (Fig. 13) reveals that the maximum Design for Assembly (DfA) score was exclusively achieved by joints with some type of locking devices, demonstrating the utility of clever "plug-and-play" mechanisms which ease the installation process and speed up on-site assembly time.

The only connections to score highest in the Design for Deconstruction (DfD) metric were **FTF06** and **BTB08**, mainly due to their promising opportunities for reuse warranted by their resilient designs, which reduce the plastic damage in framing elements. Also, the bolted steel clamps in joint **FTF06** prevent drilling any holes in beams or columns, improving the reusability of these elements.

In terms of tolerance control (TC) many of the evaluated connections scored maximum points, due to the presence of features which aid module alignment like tenons, spigots and corner fittings integrated in the structural framing of modules which can help in reducing the build-up of tolerance.

The best scoring systems in the constructional metrics are **FTF06**, **BTB09** and **CTC16** for effective combinations of demountability, reusability and tolerance control provided by bespoke features. Joint **FTF06** showcases characteristics such as the LRB, the bolted steel clamps, the guiding spigots and the decoupled design which prevents floor and ceiling beams from coming in contact with each other. Only the overall large number of bolts required to be fastened on-site prevented this system from scoring maximum points for DfA and overall. **BTB09** is easy to install due to its semiautomatic design with spring-activated pins and **CTC16** promotes the use of a simple wingnut and an interconnecting tube to clamp modules. These systems are followed closely by a mixture of connections from each joint category (**FTF12, FTF11, FTF03, BTB11, BTB08, CTC11, CTC04, PT04, LD02** and **LD01**) with equal total scores of 7, demonstrating that all types of IMCs have the potential to achieve a robust constructional performance. Despite the fact that most systems are capable of accommodating construction tolerances, the ranking reveals that there are still many systems which require improvements in terms of installation, demountability and potential for reuse.

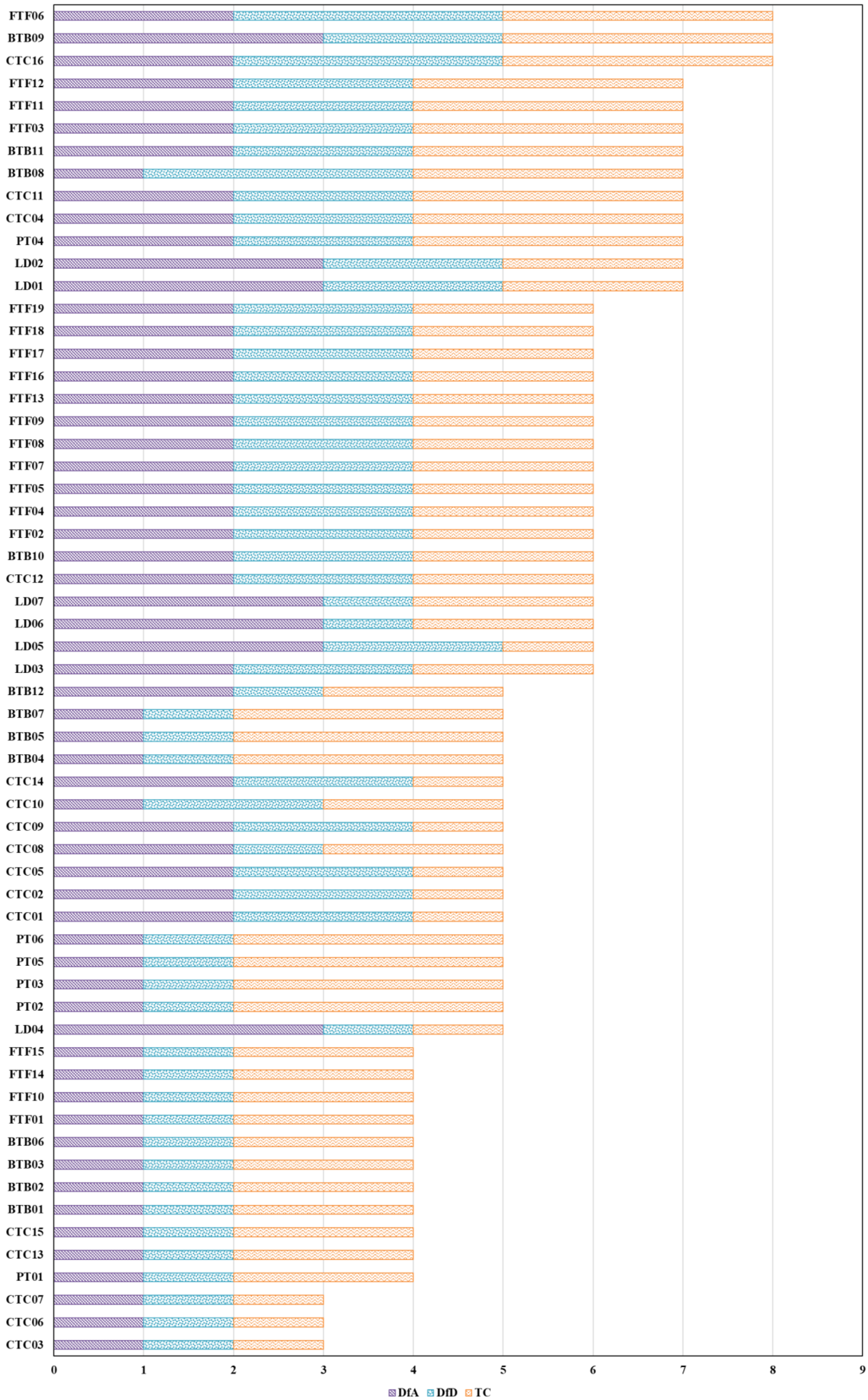

FTF06
BTB09
CTC16
FTF12
FTF11
FTF03
BTB11
BTB08
CTC11
CTC04
PT04
LD02
LD01
FTF19
FTF18
FTF17
FTF16
FTF13
FTF09
FTF08
FTF07
FTF05
FTF04
FTF02
BTB10
CTC12
LD07
LD06
LD05
LD03
BTB12
BTB07
BTB05
BTB04
CTC14
CTC10
CTC09
CTC08
CTC05
CTC02
CTC01
PT06
PT05
PT03
PT02
LD04
FTF15
FTF14
FTF10
FTF01
BTB06
BTB03
BTB02
BTB01
CTC15
CTC13
PT01
CTC07
CTC06
CTC03
0
1
2
3
4
5
6
7
8
9
DfA
DfD
TC

Fig. 13. Ranking of IMCs based on constructional metrics

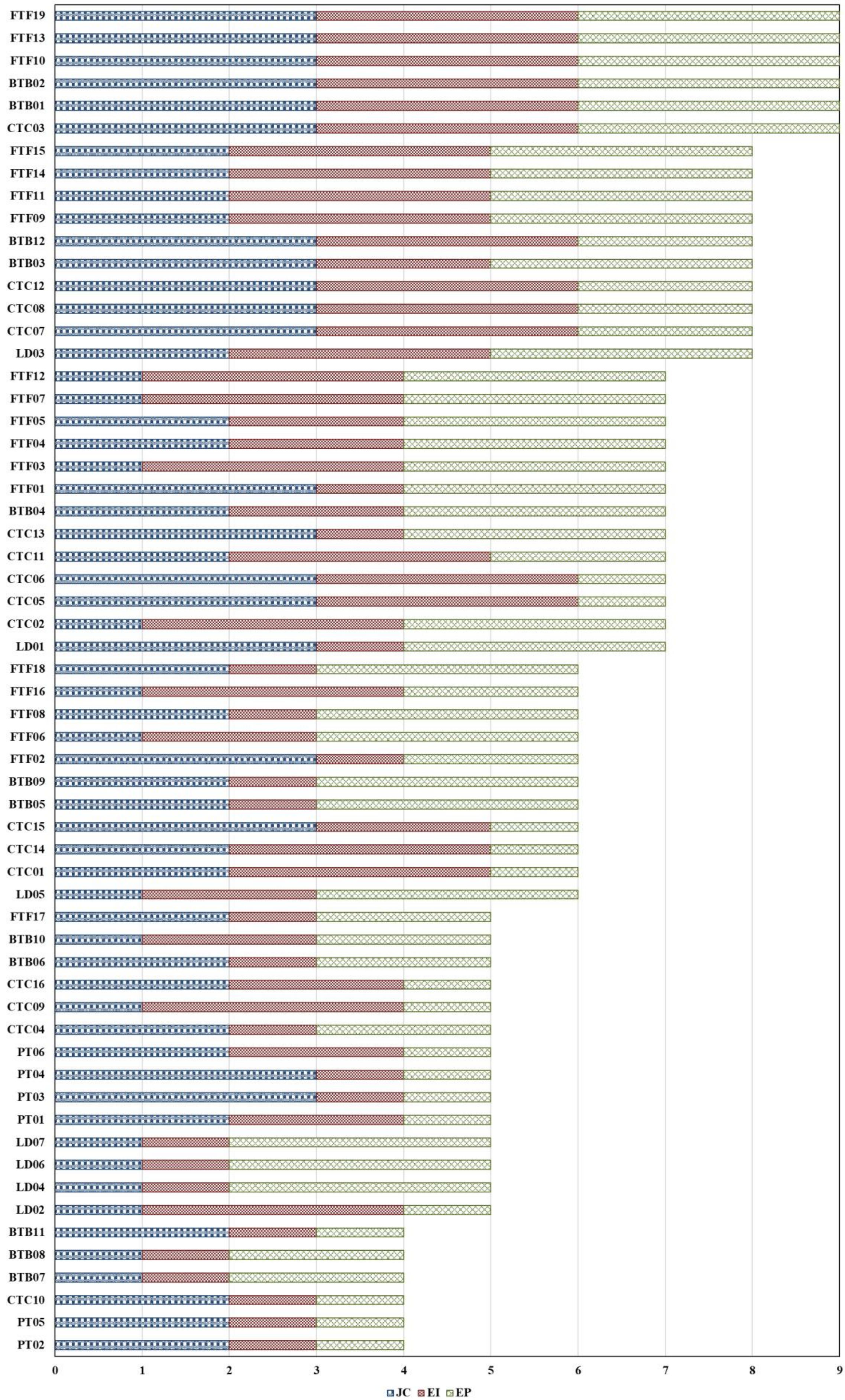
4.1.3. Ranking based on manufacturing metrics

The results from the rankings of manufacturing metrics (Fig. 14) suggest that many connections scored maximum points for joint complexity (JC), demonstrating the efficiency of common and standardised parts like bolts, plates, and corner fittings.

For ease of integration (EI) it is clear that having as few parts as possible required to assemble the final off-the-shelf connection system guarantees high scores, as well as keeping the integration of these parts simple enough, without the need for welding or precision manufacturing tools.

Highest scores in ease of pre-assembly are predominantly present in connections which can be easily pre-attached to modules in-shop, to reduce the strain on the assembly lines. An emphasis is drawn to fitting-to-fitting connections which can have parts of the connections pre-mounted inside the corner fittings of modules before delivery to site.

In the manufacturing metrics, scores were more balanced, with more than half of the evaluated connections scoring at least 7 out of 9 points. Among these, the **FTF19, FTF 13, FTF10, BTB02, BTB01** and **CTC03** joints, which scored maximum points in all metrics, showcasing their efficient Design for Manufacture and Assembly (DfMA) philosophies.


FTF19
FTF13
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BTB02
BTB01
CTC03
FTF15
FTF14
FTF11
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BTB12
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CTC12
CTC08
CTC07
LD03
FTF12
FTF07
FTF05
FTF04
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CTC04
PT06
PT04
PT03
PT01
LD07
LD06
LD04
LD02
BTB11
BTB08
BTB07
CTC10
PT05
PT02
0
1
2
3
4
5
6
7
8
9
JC
EI
EP

Fig. 14. Ranking of IMCs based on manufacturing metrics

4.1.4. Overall ranking

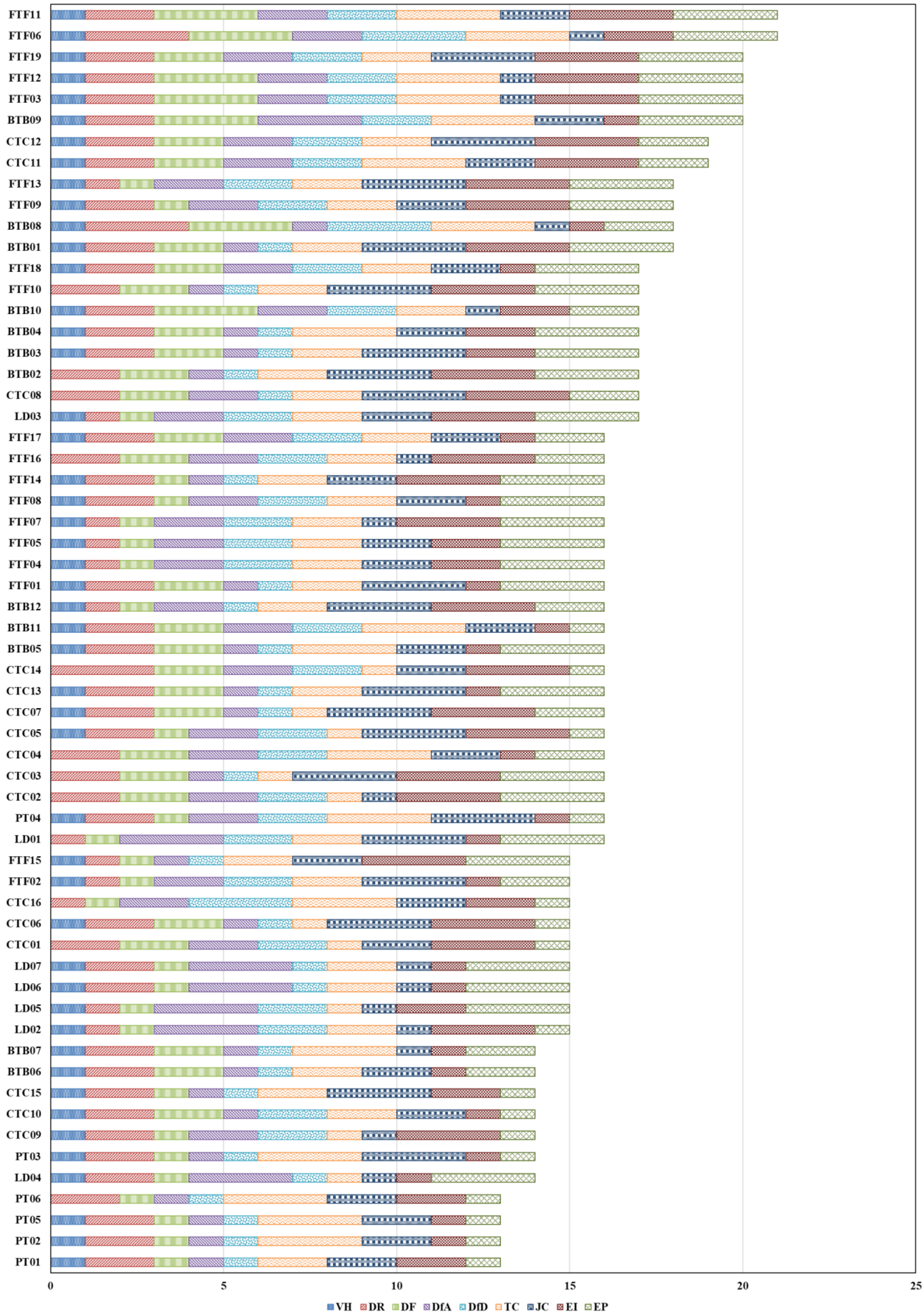
Bringing together the metrics from all three performance categories produces the ranking in Fig. 15, which highlights the following eight IMCs and their bespoke characteristics.

Overall, the highest scoring systems are **FTF06** and **FTF11** joints with totals of 21 points each. **FTF06** scored best in metrics such as DR, DF, DfD and TC due to its flexible, resilient and demountable configuration. The only improvements could be reducing the number of bolts which need to be fastened on-site, while the complexity of manufacturing and assembling the LRB part may be improved in the future as better fabrication processes are developed.

Among the next four joints are **FTF19, FTF12, FTF03**, and **BTB09**, coming second with totals of 20 points. These joints display well-balanced scores for all metrics, demonstrating robust IMCs which could be improved in terms of resilience, reuse opportunities or complexity to manufacture.

The next two IMCs scored 19 points each, achieving medium scores in almost all metrics. The **CTC11** system highlights the efficiency of common and easy to manufacture features such as interlocking pins and bolted endplates, while again adding some means of energy dissipation and damage control would help improving its resilience and demountability. Connection **CTC12** had an efficient configuration made of common parts with good energy dissipation provided by the rubber layers, yet the inclusion of self-aligning features and mitigating the difficulties in repairing or replacing the damaged endplates after an earthquake could be considered for improving its structural and constructional metrics.

In the end, it must be noted that the purpose of the ranking discussed above is not to suggest that one IMC is better than all the others in each and every aspect, as there is no fit-for-all solution in multi-dimensional problems like that of assessing the performance of IMCs. As the discussion demonstrates, the proposed framework is useful in revealing key features which make efficient designs both in terms of structural, constructional, and manufacturing aspects, while it also uncovers areas which require improvement, serving as a good starting point for future research directions.



FTF11
FTF06
FTF19
FTF12
FTF03
BTB09
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CTC11
FTF13
FTF09
BTB08
BTB01
FTF18
FTF10
BTB10
BTB04
BTB03
BTB02
CTC08
LD03
FTF17
FTF16
FTF14
FTF08
FTF07
FTF05
FTF04
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CTC13
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PT04
LD01
FTF15
FTF02
CTC16
CTC06
CTC01
LD07
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LD02
BTB07
BTB06
CTC15
CTC10
CTC09
PT03
LD04
PT06
PT05
PT02
PT01
0
5
10
15
20
25
VH
DR
DF
DfA
DfD
TC
JC
EI
EP

Fig. 15. Ranking of IMCs based on all metrics

5. Concluding remarks

This study has reviewed the relevant literature concerned with IMCs for hot-rolled steel MBSs. The state-of-the-art connections were analysed, classified, and indexed based on their connectivity systems to bring order and clarity in a voluminous and often cluttered literature. The following concluding remarks summarise the present review article: transferred

1. The present study gathered sixty IMCs from the literature and proposed a nomenclature using a rigorous and consistent classification. The main advantages of the proposed classification are represented by the comprehensive review of the existing literature and the scalability of the system, making it easy to be adopted and further expanded as new connections are proposed.

2. Given the numerous criteria which need to be considered when attempting to assess the performance of IMCs, a new multi-attribute ranking method was developed using a qualitative approach. However, the rankings hold a certain degree of subjectivity as a direct result of the authors' understanding and level of knowledge, while other interpretations may lead to somewhat different results. Nevertheless, the adoption of the proposed multi-attribute ranking system has the potential to facilitate the development of future designs, as well as to improve existing connections in low-scoring areas, serving as a useful decision-making tool for both researchers and practitioners concerned with this topic.

3. The multi-attribute ranking system revealed that the use of corner fittings, bolted joints, self-aligning/locating parts, and damage control devices are all must-have features for IMCs with all-round performance.

4. As it was shown in **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**, a great effort should be put into building data regarding the mechanical properties for as many of the existing connections in order to facilitate direct comparisons using more objective quantitative analyses.

5. The emergence of high-rise steel MBSs has uncovered a critical limitation with this type of construction, namely the lack of reliable load transfer provided by existing IMCs. This led to

the solution of welded and grouted connections which effectively create monolithic structures with good lateral stability. While these may not significantly affect installation of steel MBS, they most certainly represent a missed opportunity for the demountability or reusability of this type of buildings. While demountable joints are desired to be achieved, there is also the need for ensuring sufficient strength and stiffness of these connections, to guarantee an efficient vertical and horizontal load transfer. Smart fastener-free configurations would definitely improve the potential for automatisation of steel MBSs, yet findings from the literature suggest that in high-rise applications bolted connections are a necessary compromise to get both reliable load paths for uplift, shear or bending while also keeping installation and dismantling tasks acceptable.

6. To mitigate the poor structural response of IMCs to extreme events such as seismic actions, energy dissipative devices have been employed, yet very rarely were these integrated in the configuration of the connection itself, often preferring to introduce standalone damping devices in the modular framing instead. The use of rubber layers or LRB between steel plates connected to the modules seems to be a promising method to add damping and to absorb seismic energy locally. Also, the fast development of smart materials such as shape-memory alloys with innate properties such as superelasticity which provide passive damage control methods supports the adoption of SMAs in IMCs, emerging as a prospective research direction which was scarcely explored so far in the literature.

7. When it comes to the development of future IMC designs, more focus should be put on addressing the hindered demountability and reuse opportunities caused by the lack of seismic resilience. The potential of hyperelastic behaviour of rubber components, superelasticity of SMAs and the introduction of structural fuses to concentrate damage and dissipate energy in controlled fashion are noteworthy considerations for future research of IMCs for steel MBSs.

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