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Enhancing structural reusability and durability: A review of steel-concrete shear connector systems in modular construction

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ABSTRACT

This paper investigates the evolution and performance of advanced bolt and dowel-based shear connectors in modular and composite construction systems, focusing on steel-concrete composites, precast shear walls, modular beams, and demountable frames. Key innovations, such as high-strength friction-grip bolts (HSFGBs), threaded stud connectors, Y-stud bolts, and hybrid nut-bolt systems, are examined for their load transfer efficiency, shear resistance, and assembly ease. The study analyzes frictional mechanisms, dynamic performance, and the effectiveness of single vs. double nut configurations in structural joints. Blind bolts, reinforced hybrid bolts, and locking nuts are assessed for demountable applications. Coupler systems, including cylindrical and pretensioned bolts, are evaluated for mitigating deformations and addressing thread penetration. Innovative shear connectors, such as clamping connectors and yielding pockets, are also explored for their impact on slip capacity, stiffness, and fatigue resistance. Future research focuses on improving ductility, energy dissipation, rapid assembly, and sustainability, advancing the reusability and adaptability of modular and composite systems for more resilient structures.

Keywords: shear connectors, demountable structures.

INTRODUCTION

As global populations grow and infrastructure demands increase, the construction sector faces unprecedented challenges in balancing expansion with environmental sustainability. Steel and concrete, the bedrock materials of modern construction, present both opportunities and obstacles in this balancing act.

While steel is recyclable and concrete widely available, their traditional lifecycle, from production to demolition, comes with high energy consumption, significant carbon emissions, and material wastage.

Demountable systems in steel and concrete construction promote sustainability by enabling deconstruction and direct reuse of structural components, reducing energy-intensive recycling. Innovations in bolted and friction-based connectors facilitate modular assembly and disassembly while preserving structural integrity. Geopolymer concrete, made from industrial by-products, offers an eco-friendly alternative to Portland cement, reducing CO_2 emissions by up to 80% and incorporating construction waste. Combining demountable connections with geopolymer concrete enhances adaptability and minimizes waste. However, widespread adoption faces challenges, including the need for standardized guidelines, cost-effective solutions, and policy support to advance a circular construction economy and sustainable building practices. These issues have prompted a surge in research around demountable and reusable construction systems, offering a pathway toward a circular economy in the built environment [1].

Traditional steel recycling involves melting down materials from demolished structures to create new steel products. This process, while reducing the need for virgin materials, is energy-intensive and emits a significant amount of CO_2. However, the concept of steel reuse is evolving: instead of melting, the focus is shifting toward demountable systems that preserve the integrity of steel components for direct reuse [2–4]. Demountable steel structures offer a revolutionary approach by allowing buildings to be deconstructed, not demolished. Steel beams, columns, and other elements can be removed intact and reused in new construction, bypassing the need for energy-intensive recycling processes. This not only cuts down on waste generation but also reduces the demand for new steel production, an essential step in lowering the carbon footprint of the construction industry [5–7].

The rise of demountable connectors, particularly in composite steel-concrete structures, is pivotal in this transition. These connectors, unlike traditional welded connections, enable easy disassembly. Innovations such as bolted shear connectors and friction-based systems are seeing increasing use, allowing for modular construction that can be taken apart at the end of its lifecycle without damaging the structural integrity of steel components. As research continues, these systems could become standard in future sustainable construction projects, facilitating a shift from recycling to reuse on a large scale [8–11].

Concrete, despite being one of the most widely used materials globally, poses significant environmental challenges. The production of Portland cement, the key ingredient in conventional concrete, is a major source of CO_2 emissions, accounting for up to 8% of global emissions. Furthermore, traditional concrete production consumes large amounts of water and natural resources [12–14].

However, research into alternative materials, such as geopolymer concrete, offers promising solutions. Geopolymers, which use industrial byproducts like fly ash, slag, and even construction and demolition (C&D) waste as binding agents, significantly reduce the carbon footprint associated with traditional concrete. Compared to Portland cement, geopolymers require far less energy for production and generate up to 80% fewer emissions [15–17].

Beyond just environmental benefits, geopolymer concrete presents new opportunities for incorporating waste materials into the construction cycle. By crushing and processing C&D waste into fine aggregates or filler materials, we can create a circular economy in concrete production, where waste materials from old buildings are used to construct new ones. This approach not only conserves natural resources but also reduces the environmental burden of landfilling construction waste [18, 19].

Central to the vision of sustainable construction is the concept of deconstruction, where buildings are designed from the outset to be taken apart and reused. Demountable connections play a key role in this process. Unlike traditional fixed connections, which require on-site concrete casting and lead to permanent bonding between elements, demountable systems allow for the easy separation of structural components.

Recent innovations in dry connections between precast concrete elements are particularly exciting. These systems eliminate the need for cast-in-place joints, enabling faster assembly and disassembly on-site. Bolted connections, clip systems, and friction-based joints allow precast elements to be reused at the end of a building's life, without damaging the components. This not only reduces material waste but also opens up new possibilities for adaptable building designs, where structures can be modified or expanded over time without significant reconstruction [20–24].

The combination of geopolymer concrete with demountable connections is a game-changer for sustainable construction. By using eco-friendly concrete in conjunction with reusable steel and concrete components, we can create buildings that not only have a lower environmental impact during construction but can be fully deconstructed and repurposed at the end of their life cycle. This approach aligns perfectly with the principles of a circular economy, where materials are kept in use for as long as possible, minimizing waste and maximizing resource efficiency [25–27].

Despite the promising advances in demountable systems and sustainable materials, several challenges remain. For one, the widespread adoption of demountable connectors in steel and concrete construction requires further development of standardized design guidelines and testing procedures. Additionally, the integration of recycled materials such as geopolymer binders into mainstream construction will necessitate changes in manufacturing practices, quality control, and performance assessment [28–31].

Moreover, there are economic considerations to be addressed. While the long-term savings from material reuse and reduced environmental impact are clear, the upfront costs of demountable systems, particularly for labor and installation, may be higher than traditional methods. Research into cost-effective solutions, such as modular construction techniques and automation in assembly/disassembly, could help bridge this gap [32–36].

Ultimately, the path toward a circular construction economy hinge on collaboration between researchers, engineers, policymakers, and industry stakeholders. Governments can incentivize sustainable practices through regulations and subsidies, while the construction industry must continue to invest in research and development of reusable materials and systems.

INNOVATIONS IN DEMOUNTABLE CONNECTORS: A COMPREHENSIVE TYPOLOGY

The exploration of innovative advancements in demountable shear connectors in modular construction highlights a range of connection technologies defined by their design and performance characteristics. It begins with bolt-only solutions, showcasing friction-grip bolts that provide exceptional modular strength, threaded stud connectors that optimize load paths, and Y-stud bolts that introduce geometric innovations. The discussion then shifts to nut-bolt hybrid systems, emphasizing the efficiency of single and double nut configurations, along with discreet blind bolts and hybrid bolts with reinforced steel blocks that enhance load capacity.

T-shaped embedded nut connectors offer simplicity and strength, while advanced locking nut mechanisms facilitate easy disassembly. Rectangular coupler systems, including cylindrical, pretensioned, and injection-based designs, expand bolting solutions, featuring yielding pockets for controlled deformation and clamping couplers for long-term stability. Finally, tapered coupler systems highlight friction-based and steel-yielding connectors adept at managing dynamic loads. Together, these advancements pave the way for modular beams that are robust, adaptable, and sustainable, establishing a new standard in structural engineering.

Bolt-only solutions: exploring nut-free connector technologies

The evolution of bolt-only solutions in shear connection technology represents a significant advancement in modular construction, as these designs eliminate the need for embedded nuts, streamlining assembly processes. Friction-grip bolts, characterized by their ability to transmit shear forces through friction rather than traditional bearing methods, offer substantial modular strength and facilitate rapid assembly. Researches highlighted the superior load-bearing capacities of friction-grip designs compared to conventional connections, making them particularly effective in high-demand applications.

Threaded stud connectors take this innovation further by optimizing load paths, allowing for efficient force distribution across the structure. By providing a continuous load path, these connectors enhance the structural integrity of composite systems. Y-stud bolts introduce geometric enhancements, which not only improve the load transfer capabilities but also reduce the overall weight of the connections. The versatility and effectiveness of these nut-free technologies underscore their potential to revolutionize connection methods in modern structural engineering.

Friction-grip bolt designs for modular strength

Friction-grip bolts (HSFGBs) as shown in Fig. 1, stand out as a pivotal innovation in the realm of modular construction, offering a robust solution for shear connections in composite beams. The mechanism of load transfer in HSFGBs relies heavily on the friction developed between the bolt's shank and the connected components, such as steel beams and concrete slabs. Studies have shown that these bolts exhibit minimal slippage under initial loads, ensuring a stable connection that maintains rigidity during service. Key factors influencing the performance of friction-grip bolts include the diameter and tensile strength of the bolts, which directly correlate with the shear capacity of the connection. Furthermore, the arrangement and preload of the bolts significantly impact their effectiveness; HSFGBs that are preloaded adequately demonstrate enhanced initial stiffness, although higher preloads can diminish slip capacity and ductility. Thus, careful consideration during installation and maintenance is essential to optimize the performance of these connectors in practice.

Threaded stud connectors: reinventing the load path

Threaded stud connectors as shown in Figure 2 represent a transformative approach in managing load paths within steel-concrete composite

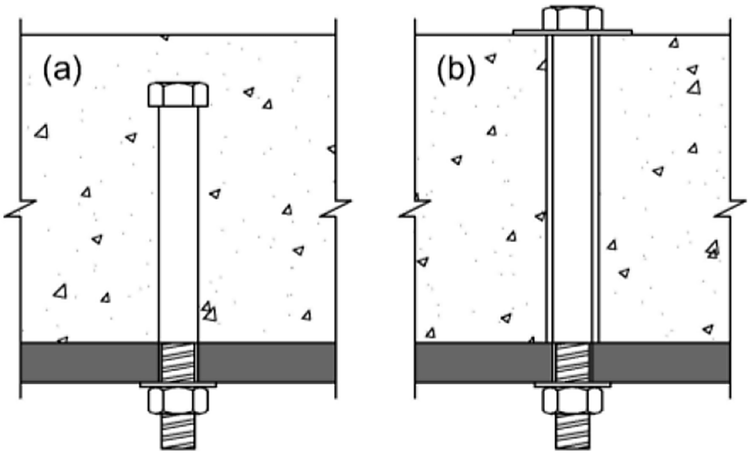

Figure 1. No embedded nut (a), friction grip bolt (b) [8]

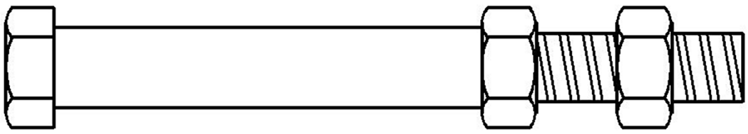

Figure 2. Threaded stud connectors [11]

systems. By allowing for direct anchorage into concrete, these connectors create a reliable interface that effectively distributes shear forces throughout the structural assembly. The design enables easy adjustments during construction, facilitating precise alignment and enhancing overall structural performance. Recent advancements have highlighted the potential for threaded stud connectors to accommodate dynamic loading conditions, demonstrating superior performance under both static and cyclic loading scenarios. Researchers have emphasized the importance of stud placement and configuration, noting that their spatial arrangement can significantly influence the connector's load-bearing efficiency. This innovation not only optimizes structural integrity but also paves the way for enhanced design flexibility in modern engineering applications.

Y-stud bolts: geometric enhancements for composite systems

Y-stud bolts as shown in Figure 3 are emerging as a highly efficient solution for enhancing the performance of composite systems through innovative geometric design. Their unique shape promotes effective load transfer while minimizing stress concentrations at critical connection points. The design allows for more effective distribution of forces within the composite structure, addressing common weaknesses found in traditional shear connectors. Furthermore, Y-stud bolts facilitate easier assembly and disassembly, aligning perfectly with contemporary demands for modularity and sustainability in construction. Research has indicated that the use of Y-stud bolts can lead to improved fatigue resistance and longevity of connections, as the geometry helps mitigate localized failures often seen in standard bolt

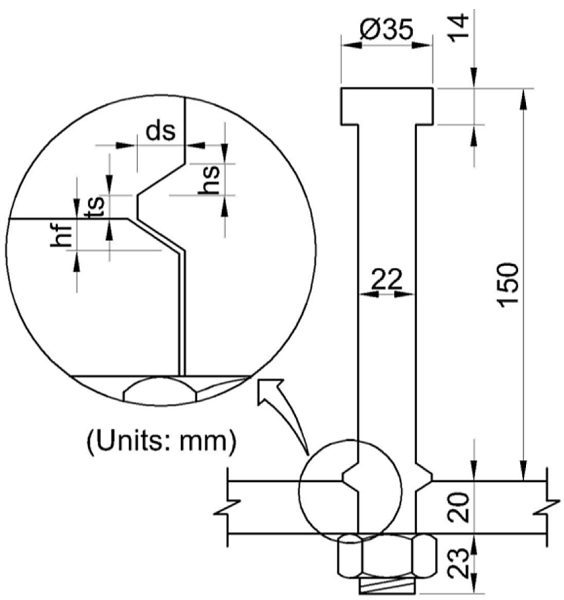

Figure 3. Stud bolts [61]

configurations. By integrating these advanced designs, engineers can create more resilient and adaptable structures that meet the challenges of modern construction.

Nut-bolt hybrid systems: Precision fastening for advanced performance

Nut-bolt hybrid systems represent a critical evolution in connection technologies, particularly in applications demanding high precision and reliability. These systems incorporate both nuts and bolts to achieve enhanced performance characteristics, such as increased load capacity, improved stiffness, and better overall structural behavior. The strategic use of nuts in conjunction with bolts not only facilitates effective load transfer but also allows for adjustments during installation, ensuring optimal alignment and minimizing the risk of connection failure under dynamic loads.

Moreover, nut-bolt hybrid systems are designed to address common issues associated with traditional bolted connections, such as loosening over time and vulnerability to cyclic loading. The incorporation of advanced materials and innovative designs in these systems contributes to their resilience, making them suitable for demanding environments. As a result, nut-bolt hybrid systems are becoming increasingly popular in modern structural engineering, offering a balanced solution that combines strength, flexibility, and ease of maintenance.

Single and double nut configurations: Comparative efficiency

Single and double nut configurations within nut-bolt hybrid systems as shown in Fig. 4 each exhibit distinct performance characteristics that influence their application in structural connections. Single nut configurations are straightforward and cost-effective, facilitating quick installation and adequate performance under moderate loads. However, they may experience loosening over time due to vibrations and repeated loading, leading to potential failures if not regularly monitored.

On the other hand, double nut configurations enhance connection stability and shear resistance by utilizing an additional nut as a locking mechanism. This design significantly improves performance under cyclic loading, reducing the likelihood of slippage and ensuring a more rigid connection. While the double nut system offers increased stiffness and durability, it also introduces complexity in installation, which may require additional labor and careful alignment to ensure proper engagement. The choice between single and double nut configurations ultimately depends on the specific loading conditions and maintenance capabilities of the structure.

Blind bolt innovations for concealed connections

Blind bolt innovations as shown in Figure 5 represent a significant advancement in nut-bolt hybrid systems, especially for concealed connections where access is limited. These connectors can be installed from one side, allowing for efficient assembly in tight spaces or during the retrofitting of existing structures. The performance of blind bolts is notable for their ability to maintain high shear strength while simplifying the installation process, which is crucial for time-sensitive construction projects.

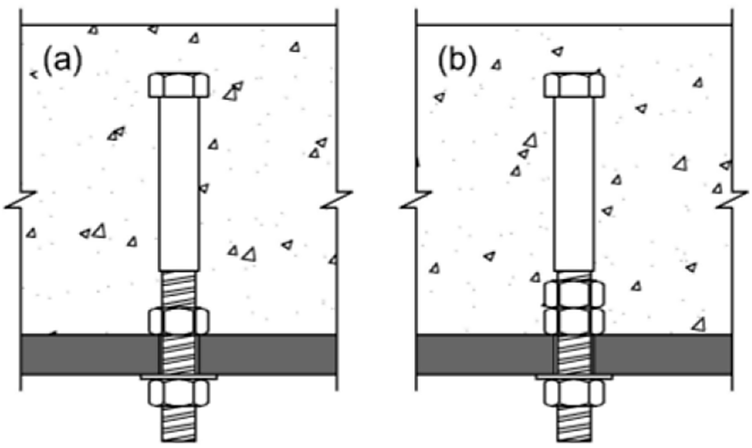

Figure 4. Single (a) and double nut configurations (b) [8]

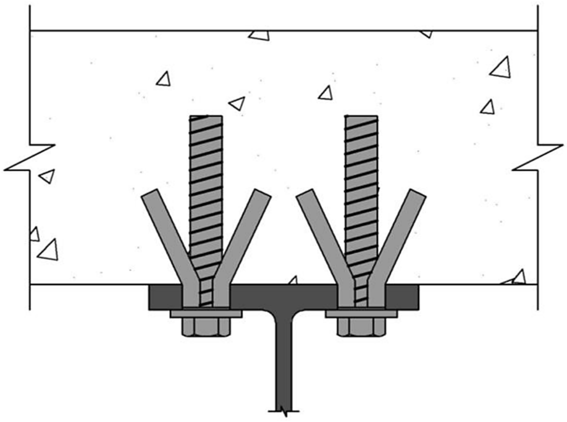

Figure 5. Blind bolt concealed connections [16]

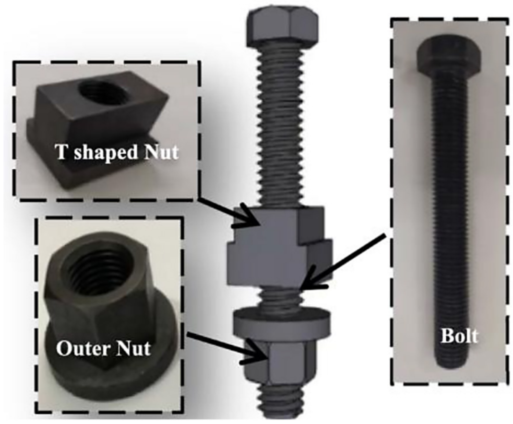

Figure 6. T-Shaped embedded nut connectors [9]

Despite their advantages, blind bolts can exhibit variability in initial stiffness compared to traditional bolts due to their unique expansion mechanisms. This variability may lead to challenges in maintaining connection integrity under dynamic loads, particularly in applications where movement or vibration is anticipated. Recent advancements in blind bolt design have aimed to address these concerns by improving load distribution and reducing the risk of failure through innovative reinforcement techniques. Overall, blind bolt innovations offer a promising solution for modern construction needs, balancing ease of use with robust performance.

Hybrid bolts with reinforced steel blocks: Extending load capacity

Hybrid bolts as shown in Fig. 6 featuring reinforced steel blocks significantly enhance the load capacity and performance of nut-bolt hybrid systems. The integration of steel blocks not only reinforces the connection but also aids in distributing loads more evenly across the connected elements. This design minimizes stress concentrations and reduces the risk of localized failure, making it particularly effective in high-stress applications such as bridges and industrial structures.

The primary performance benefit of these hybrid bolts lies in their superior shear and tensile resistance, which enables them to withstand significant loading conditions without compromising structural integrity. However, the introduction of reinforced steel blocks also increases the complexity of installation, requiring precise alignment and careful placement to ensure the connection functions as intended. Additionally, while these bolts provide excellent load-bearing capacity, they may limit the ductility of the connection, raising concerns about potential brittle failure under extreme conditions. Nonetheless, hybrid bolts with reinforced steel blocks offer a reliable solution for structures requiring enhanced performance and durability.

T-Shaped embedded nut connectors: Merging strength and simplicity

T-shaped embedded nut connectors as shown in Figure 6, combine strength and simplicity in their design, offering substantial performance benefits in structural applications. By embedding nuts directly into the concrete, these connectors provide a secure anchor point for bolts, which significantly enhances both shear and tensile resistance. This design not only improves load distribution but also reduces the likelihood of concrete crushing around the connection, leading to enhanced durability.

The performance of T-shaped embedded nut connectors is characterized by their ease of installation, as they can be pre-embedded during the concrete pouring process. This simplifies the assembly process and minimizes the need for complex alignment during construction. However, one notable drawback is the difficulty in accessing or replacing embedded connectors, which poses challenges for maintenance and repair over the structure's lifespan. Additionally, while these connectors excel in load distribution, they may exhibit reduced flexibility, increasing the risk of brittle failure under high loads. Despite these limitations, T-shaped embedded nut connectors are an effective choice for applications prioritizing strength and efficiency.

Locking nut mechanisms for reusable beam connections

Locking nut mechanisms are an innovative component of nut-bolt hybrid systems as shown in Figure 7, particularly beneficial for reusable beam connections. These mechanisms are designed to prevent loosening under dynamic loading conditions, ensuring the connection remains secure over time. This capability is essential in modular construction, where components may be disassembled and reassembled multiple times without compromising structural integrity.

The performance of locking nut mechanisms is notable for their ability to maintain connection stability even under cyclic or fluctuating loads. This minimizes the need for regular inspections and maintenance, addressing one of the common challenges faced by traditional bolted connections. However, the complexity of these systems can present installation challenges, requiring skilled labor and precise alignment to ensure proper engagement. Furthermore, while locking mechanisms enhance durability, they may also reduce ductility, increasing susceptibility to brittle failure in extreme loading scenarios. Despite these concerns, locking nut mechanisms provide an effective solution for applications where reusability and long-term performance are critical.

Rectangular coupler systems: Expanding the range of demountable bolting technologies

Rectangular coupler systems represent a transformative advancement in bolted connection technology, designed to overcome the limitations of conventional bolted connectors that lack integrated couplers. These systems offer a remarkable array of benefits, including superior load transfer capabilities, adaptability to diverse bolt sizes and materials, streamlined installation processes, enhanced durability in adverse conditions, and the added advantages of removability and reusability. The classification of rectangular coupler systems introduces six groundbreaking designs:

- cylindrical coupler system (CS),
- pretensioned bolt with coupler system (PBCS),
- injection bolt with a coupler system (IBCS),
- yielding pocket (YP),
- clamping connector (CC),
- locking-bolt demountable (LBD) shear connector.

Collectively, these innovations not only enhance the performance of bolted connectors but also pave the way for a more sustainable and efficient approach to construction.

Cylindrical couplers: Simple solutions for modular beams

The cylindrical coupler system (CS) as shown in Figure 8 emerges as a response to the challenges posed by creep and shrinkage in conventional bolted connections. It integrates a cylindrical steel tube, which work cohesively

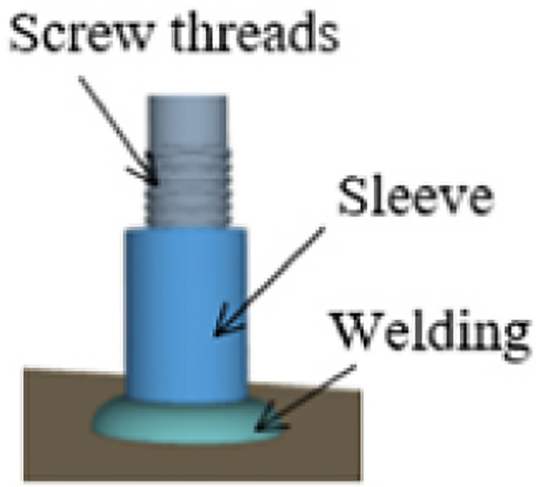

Figure 8. Cylindrical couplers [6]

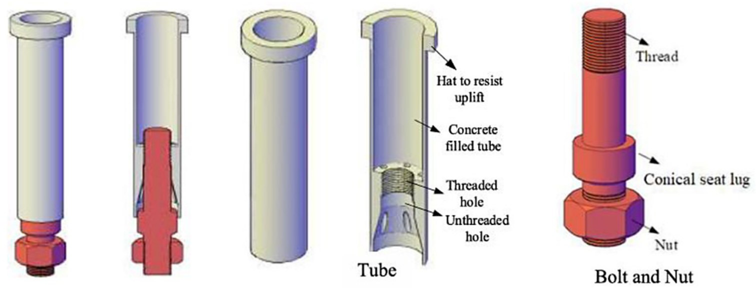

Figure 7. Locking nut mechanisms [10]

to optimize shear force management. This innovative design emphasizes enhancing the performance of shear connectors, facilitating superior stability without compromising the integrity of the surrounding concrete or steel elements. The initial rigidity of the CS remains intact until the frictional forces are surpassed, allowing for a measured slip. This capacity for controlled slip is indicative of the system's ability to balance performance and resilience effectively. The CS's strength and slip characteristics significantly outperform those of traditional welded studs, making it a compelling option for modern construction applications. However, the design's initial stiffness can be improved, indicating potential for future advancements.

Pretensioned systems for load-optimized connections

Advancing from the principles established in the CS, the pretensioned bolt with coupler system (PBCS) innovatively integrates high-strength couplers to prevent potential damage profile. By ensuring that wear and damage are confined to the replaceable bolts, this system effectively protects the nonreplaceable couplers from degradation, thereby enhancing overall connection longevity.

While the PBCS exhibits certain advantages, such as increased load-bearing capability, its initial stiffness remains lower than that of the CS due to the preload generated by the interconnected bolts. This dynamic creates an interesting balance between slip performance and load management, warranting further exploration into optimizing its design for improved efficiency in load transfer.

Injection bolt systems: Enhancing structural efficiency

The injection bolt with a coupler system (IBCS) as shown in Figure 9 innovatively incorporates epoxy resin to fill gaps between the bolt and steel beam, mitigating issues related to thread penetration. This application allows for greater hole clearances and effectively reduces slip, contributing to improved structural integrity.

Despite its benefits, the IBCS's slip capacity of 3.76 mm may not meet all design requirements, particularly those necessitating higher ductility levels as per EC4 standards [43]. However, its capacity to minimize thread penetration makes it a valuable option in specific applications where traditional penetration poses significant risks. Implementing rigorous quality control measures during installation will be crucial to realizing its full potential.

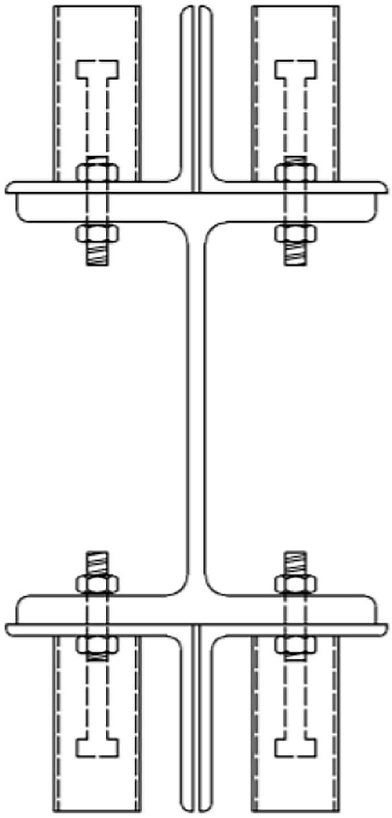

Figure 9. Injection bolt [20]

Yielding pockets for controlled deformation

The yielding pocket (YP) as shown in Figure 10 introduces a novel approach to promoting the reuse of materials in construction. This design facilitates the easy disassembly of composite structures, addressing challenges associated with material reuse.

Experimental findings indicate that damage predominantly occurs within the vertical strips of the YP, while the surrounding concrete remains unscathed, highlighting the system's capacity for sustainable practices. The YP's superior strength and ductility compared to traditional welded studs illustrate how innovative design can enhance both performance and sustainability in construction.

Clamping couplers: Securing long-term performance

Addressing alignment issues commonly faced during the integration of precast concrete slabs with steel beams, the clamping connector

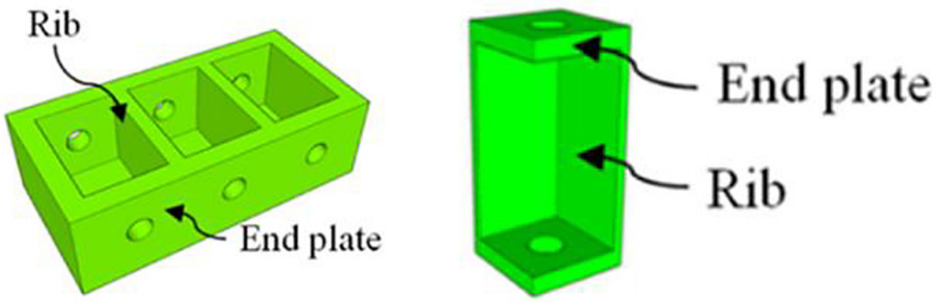

Figure 10. Yielding pockets [31]

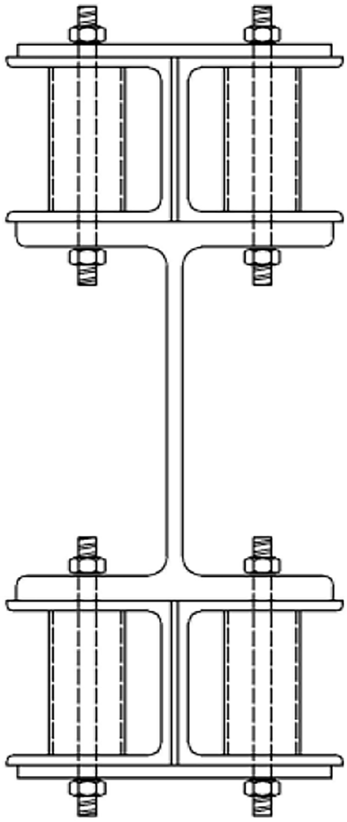

Figure 11. Clamping couplers [20]

(CC) as shown in Figure 11 employs clamps and high-strength T-bolts to ensure secure connections. The CC is designed to deliver substantial initial stiffness, attributed to the friction among its components.

Research demonstrates that while M20 bolts may suffer from strength loss under large slip conditions, M24 bolts exhibit greater resilience due to their design. The CC's capacity for slip, ±25.4 mm, exemplifies its robust deformation potential, making it an attractive option for dynamic construction environments.

Locking-bolt systems: The future of high-performance modular construction

The locking-bolt demountable (LBD) shear connector as shown in Figure 12 offers a solution to the persistent issue of alignment discrepancies between concrete slabs and steel flanges. The system combines a grout-filled tube with a partially threaded bolt, establishing a reliable locking mechanism that effectively minimizes initial slippage.

This innovative approach not only enhances connection reliability but also simplifies the disassembly process for composite floor systems, promoting material reuse. Experimental studies have revealed that failure modes primarily involve concrete crushing, indicating that the system's performance is significantly influenced by the strength of the concrete used. The LBD's impressive slip capacity positions it as a robust and effective choice for modern composite beam applications, reflecting a commitment to both performance and sustainability.

Tapered coupler systems: Dynamic load management in modular beams

The quest for optimal load transfer, efficient installation, and enhanced performance in modern construction practices has catalyzed the development of innovative bolt connections, particularly those employing tapered coupler systems. This evolution in fastening technology addresses critical demands within the industry, leading to the emergence of several advanced connection types:
- locking nut shear connectors,
- friction-based shear connectors,
- steel-yielding demountable shear connectors,
- tapered iron shear connectors.

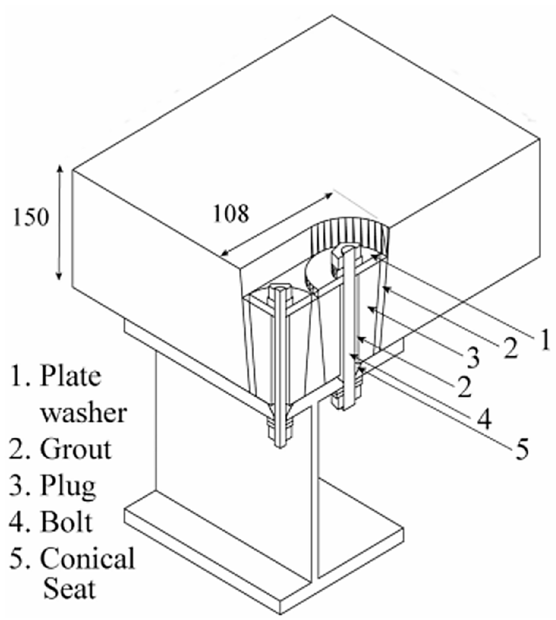

Figure 12. Locking-bolt system [22]

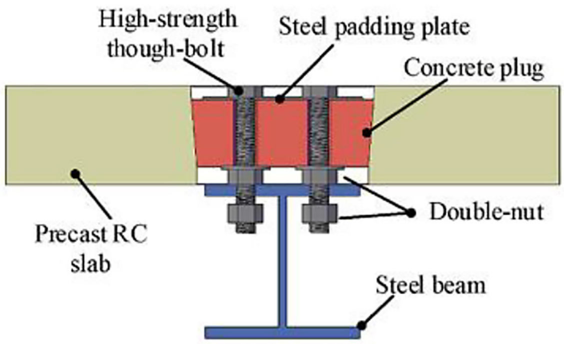

Figure 13. Locking nut high-performance connection [19]

Each type of connector features a tapered interface that not only optimizes load distribution but also outperforms traditional welding methods, significantly enhancing the overall resilience and longevity of structural assemblies.

Advanced locking nut solutions for high-performance beams

The locking nut (LN) shear connector as shown in Figure 13 stands as a hallmark of engineering innovation, streamlining assembly through a unique double-locking configuration. This design not only mitigates alignment issues during installation but also promotes structural stability under load. However, the challenge of disassembly arises due to the strong bonds formed between the components, which can complicate maintenance and repair operations. Experimental evaluations demonstrate that the LN shear connector effectively navigates frictional challenges at the steel-concrete interface, facilitating a controlled sliding mechanism. This results in a gradual failure process, enhancing safety and predictability during extreme load conditions. With superior stiffness and slip capacity compared to welded studs, the LN connector sets a new standard for bolted connections in high-performance applications.

Friction-based connectors: Reliable performance under repetitive loading

The friction-based (FB) shear connector as shown in Figure 14 represents a significant leap forward by eliminating the conical nut and integrating a retaining washer while utilizing grout to fill the hole. This adaptation reduces tolerances during construction, thereby improving the reliability of connections. Nevertheless, challenges persist regarding grout removal during replacement, highlighting the importance of ongoing research into material properties and assembly techniques.

Studies reveal that the FB shear connector mirrors the shear transfer mechanism of its predecessor while offering improved stiffness and

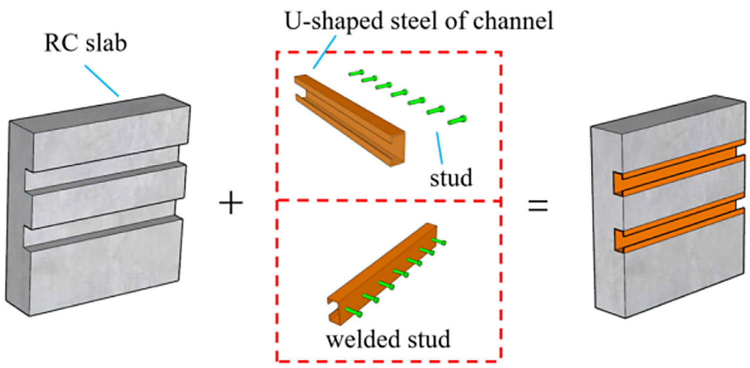

Figure 14. Friction-based connector [32]

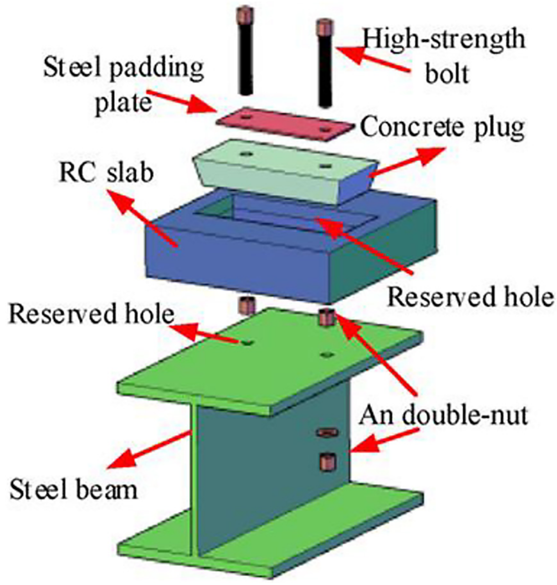

Figure 15. Steel-yielding connector [23]

ultimate strength over welded connections. The buffer zone created by the grout further enhances its slip capacity, showcasing the potential for friction-based systems to revolutionize connection design in dynamic environments.

Steel-yielding connectors: Blending flexibility and durability

The steel-yielding demountable (SYD) shear connector as shown in Fig. 15 introduces tapered ultra-high-performance concrete (UHPC) blocks, effectively bridging the gap between assembly efficiency and structural performance. This innovative design minimizes sliding through the use of conical nuts, ensuring a more stable connection under varying load conditions. Observations indicate that while initial damage occurs at the UHPC block, the overall integrity of the connection is preserved, demonstrating the resilience of this approach.

The SYD shear connector's capacity to exceed the slip limits of conventional systems underscores the potential for advanced materials to enhance structural safety and performance. However, further optimization of stiffness and strength remains a critical focus area for ongoing research.

Tapered bolt systems for optimized joint strength

Addressing the disassembly challenges inherent in friction-based systems, the tapered iron (TI) shear connector as shown in Fig. 16 has been meticulously designed to facilitate ease of disassembly while maintaining structural

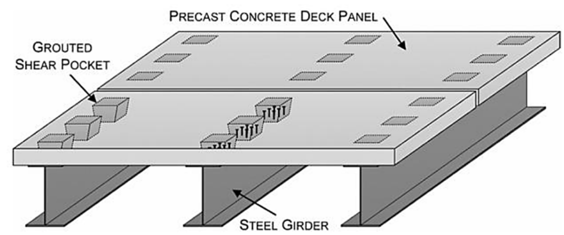

Figure 16. Tapered bolt system [8]

integrity. The innovative vertical seam in the sleeve accommodates circumferential deformation, mitigating alignment issues that may arise during installation.

Experimental insights suggest that the TI shear connector exhibits minimal slip during initial loading, with shear failure localized at the bolt intersections rather than throughout the assembly. This characteristic not only enhances the durability of the connection but also offers significant advantages in terms of maintenance and adaptability in the field.

CUTTING-EDGE PRACTICES IN STRUCTURAL JOINT DESIGN AND IMPLEMENTATION

Current structural engineering practices face sustainability challenges, particularly in managing structures at the end of their life. Despite the durability of steel and concrete components, demolition typically involves destructive methods, leading to energy-intensive steel recycling and landfilling of other materials. This process wastes resources and increases carbon emissions. To promote sustainability, structures must be designed for future reuse. However, fully demountable connections in reinforced concrete (RC) structures are not yet widely adopted due to limited understanding of their structural behavior and safety. Recent efforts focus on precast concrete systems with semi-dry connections, which facilitate controlled deconstruction. While these connections, such as dowel shear and moment-resisting systems, enable easier disassembly, they also pose challenges like the need for mechanical disruption of concrete and steel cutting. As these systems gain traction, refining connection technologies and establishing standardized protocols for deconstruction and reassembly are crucial to advancing sustainable practices in structural engineering.

Table 1. Shear connector technologies

Connector type	Key features	Applications	Advantages
High-strength friction-grip bolts (HSFGBs)	Frictional load transfer, high shear resistance	Steel-concrete composite structures	Improved load transfer, high performance
Threaded stud connectors	Threaded design for secure anchoring	Precast shear walls, modular beams	Easy assembly, reliable shear connection
Y-stud bolts	Unique geometry for enhanced load capacity	Composite systems, demountable frames	Enhanced slip resistance, fatigue performance
Hybrid nut-bolt configurations	Combination of nut and bolt for flexible assembly	Various modular connections	Improved structural integrity, ease of installation
Blind bolt systems	Concealed connections for aesthetics and simplicity	Demountable structures, concealed connections	Flexibility, reusability in modular designs
Reinforced hybrid bolts	Increased strength through composite reinforcement	Heavy-duty applications in precast and modular systems	Greater durability and load capacity
Clamping connectors	Direct clamping action for load transfer	Beam-to-column joints	Simple installation, effective load distribution
Yielding pockets	Controlled yielding for energy dissipation	Seismic-resistant structures	Enhanced energy absorption, improved ductility
Cylindrical couplers	Rotationally symmetrical design for ease of installation	Modular construction systems	Simplified assembly, reduced construction time
Pretensioned bolt systems	Pre-tensioned design for reduced long-term deformation	Steel-concrete assemblies	Mitigates creep and shrinkage, enhances stability

Table 1 summarizes various bolt and dowel-based shear connectors, highlighting their key features, primary applications, and advantages in modular and composite construction systems. These connectors offer distinct benefits, from improved load transfer and durability to ease of installation and flexibility for demountable structures.

Advanced shear dowel connections for enhanced load transfer

Innovative shear dowel connections have emerged as a transformative approach in the design of precast reinforced concrete (RC) structures, significantly improving load transfer mechanisms between structural components. These connections utilize a method where dowel bars or bolts are strategically placed within pre-drilled holes of precast elements, subsequently filled with a high-strength grout. This process establishes a secure bond that enhances the structural integrity of the connection. Recent advancements in connection design have focused on optimizing the configuration and dimensions of dowels to increase shear resistance and mitigate the likelihood of failure during dynamic load scenarios, such as seismic events.

Research has shown that variations in dowel geometry, including different lengths and diameters, can play a critical role in load distribution and overall structural behavior. In particular, the integration of advanced composite materials within the grout matrix has demonstrated improvements in ductility and crack resistance, addressing common vulnerabilities associated with traditional dowel systems. This innovative approach not only facilitates efficient load transfer but also promotes long-term durability and resilience of the connections, thereby paving the way for more robust precast RC structures capable of withstanding rigorous loading conditions.

Continuity bars in seismic moment-resistant frames: Innovations and challenges

Continuity bars serve as a vital element in the design of seismic moment-resistant frames, enabling the effective transfer of flexural stresses between beams and columns. These bars extend beyond the terminations of structural elements, forming welded connections that are subsequently enveloped in cast-in-place concrete to enhance joint stability. This conventional methodology facilitates shear transfer through strategically designed shear keys, as highlighted in recent studies on moment-resisting connections. However, the use of continuity bars presents inherent challenges, such as susceptibility to corrosion and alignment difficulties during installation, which can compromise structural performance over time.

To address these issues, ongoing research and innovation are focusing on prefabricated continuity systems that streamline the construction process while enhancing the overall effectiveness of moment-resisting frames. By utilizing modular components and innovative fastening techniques, engineers are seeking to improve the speed and accuracy of construction, reducing labor costs and minimizing the potential for human error. Furthermore, integrating advanced materials with self-sensing and self-healing properties into continuity bar systems may enhance the resilience and longevity of these connections, ensuring that they maintain their structural integrity in the face of evolving environmental challenges.

MODULAR CONSTRUCTION USING DEMOUNTABLE JOINT SYSTEMS

Modular construction has revolutionized the structural engineering industry by allowing the off-site fabrication of structural components that can be assembled with precision and speed onsite. The critical factor in modular construction lies in the efficacy of demountable joint systems, which allow these prefabricated components to connect without compromising strength or stability. A sound understanding of load transfer, stiffness compatibility, and ductility is essential to design these connections. This section explores various types of demountable joint systems, focusing on their performance under load-bearing conditions and their potential for innovation in the industry.

Beam-to-column connections for rapid assembly

Beam-to-column connections as shown in Figure 17 are pivotal in ensuring the structural integrity and performance of precast reinforced concrete (RC) systems. These connections must efficiently transfer loads between structural elements while accommodating movement due to seismic activity and other dynamic forces. The complexity of stress transfer mechanisms in these connections, involving bending moments and shear forces, makes them particularly challenging to design and construct.

In precast RC structures, connections are often subjected to various loading conditions, including vertical loads, lateral loads from wind or seismic forces, and temperature-induced movements. The stresses transferred through these connections can be categorized as flexural and shear stresses, both of which must be effectively managed to prevent premature failure.

Three innovative non-prestressed dry connections designed to enhance the performance of beam-to-column connections in precast systems, utilizing threaded pre-tensioned bolts and embedded steel plates [41]:

- Connection A (end plate connection): this configuration features a steel end plate embedded in the beam, allowing for direct anchorage of the beam's main reinforcement. The design facilitates a robust path for stress transfer, effectively converting tensile forces in the beam's reinforcement into compressive forces in the steel plate. During seismic testing, this connection demonstrated superior performance, exhibiting a plastic hinge formation away from the beam end, indicating that the connection was stronger than the beam's inherent capacity. Experimental results revealed a maximum lateral load capacity ranging from 175 kN to 185 kN at a lateral drift of approximately 4%, demonstrating its resilience and energy dissipation capability under dynamic loading.
- Connection B (angle connection): this connection utilizes an angle plate to connect the beam to the column. The design relies on the interaction between the beam's reinforcement and the angle plate, with tensile forces being transmitted through the surrounding concrete and bolts. However, this path introduces complexity, leading to higher stress concentrations and potential cracking, particularly in the concrete surrounding the connection. The maximum lateral load capacity observed for Connection B ranged from 110 kN to 155 kN at a drift of 2%, reflecting its relatively reduced stiffness and ductility compared to Connection A.
- Connection C (tube connection): similar in concept to Connection B, this connection encases the beam with a steel end angle plate. The performance of Connection C was closely aligned with Connection B, exhibiting a maximum lateral load capacity of 110 kN to 140 kN at a drift of 2%. This similarity suggests that the encasement does not significantly enhance strength or ductility. Both Connection B and Connection C were influenced by the fill material used in the contact zone, with rubber sheets and epoxy resin leading to premature slip, further emphasizing the importance of material selection in achieving optimal connection performance.

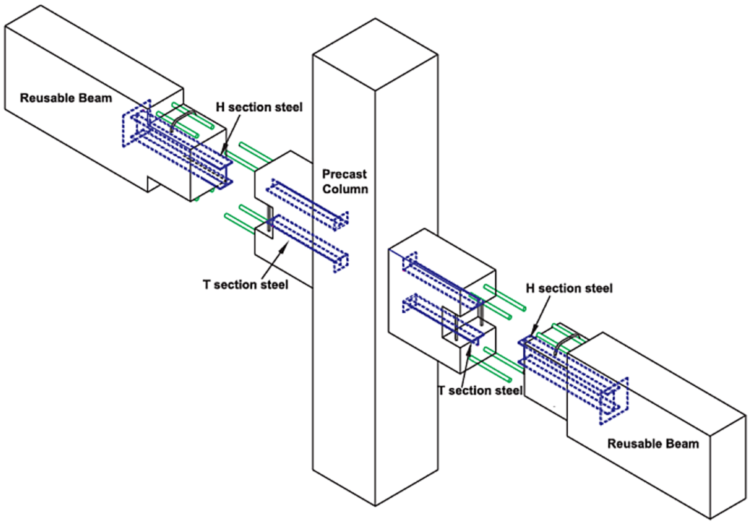

Figure 17. Beam-to-column connections [7]

The fundamental behavior of these connections can be understood through basic structural engineering principles. The connection's ability to transfer loads hinges on the interaction between the concrete and steel components. For Connection A, the embedded steel end plate provides a direct path for tensile forces, enhancing moment transfer and reducing the likelihood of failure at the interface. In contrast, the more convoluted paths in Connections B and C lead to increased stress concentrations in the concrete, diminishing their overall effectiveness.

In terms of seismic performance, the formation of plastic hinges at strategic locations within the structure is crucial for energy dissipation during events. Connection A's ability to localize plasticity away from the connection itself is a significant advantage, reducing the risk of brittle failure and contributing to the overall resilience of the structure.

Efficient wall to wall joint techniques for modular systems

The efficiency of wall-to-wall joint techniques in modular construction is critical for ensuring structural integrity, minimizing assembly time, and enhancing the overall performance of the building system. One promising approach, involves employing concrete dry connections that can be optimized for improved performance and durability. When pretensioned bolts are employed, they enhance the load transfer capabilities of the joint. The pretensioned bolts create a clamping force that helps maintain contact between the connected elements, thereby reducing slip and improving the overall stiffness of the joint. This arrangement effectively mitigates relative displacement at the connection under lateral loads, which is particularly beneficial during seismic events.

The primary advantage of utilizing steel plate connectors lies in their ability to effectively distribute flexural stresses across the edges of the wall sections. The steel plate connection provides an effective surface area for stress transfer, which is essential in scenarios where significant bending moments are expected. This configuration minimizes stress concentrations at the edges of the precast elements, thereby enhancing the resilience of the joint against potential failure modes such as cracking or shear sliding. In situations where shear stresses are predominant, such as in the case of lateral loads from wind or seismic activity, incorporating embedded steel plates within the wall sections becomes preferable. These plates enhance the shear transfer capacity of the joint by providing a rigid interface that can effectively resist sliding and rotation. The plates can be positioned in a way that allows them to engage directly with the wall reinforcement, providing additional confinement to the joint region. This confinement is crucial for maintaining the integrity of the concrete in the vicinity of the joint, which is often subject to high shear forces and potential cracking.

A schematic representation of wall-wall joint technique can be observed in Figure 18. To

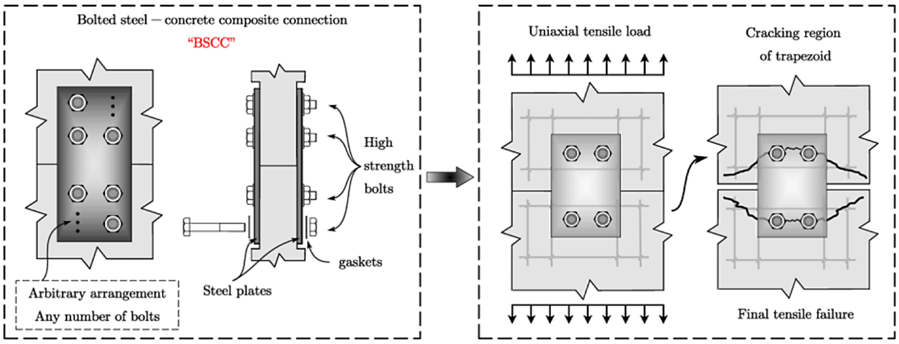

Figure 18. Wall to wall joint techniques [1]

fully understand the performance characteristics of these wall-to-wall connections, experimental investigations should focus on several key parameters. Varying the thickness of the embedded steel plates can influence both the stiffness and strength of the joint. Thicker plates may provide better shear resistance but can also increase the weight and complexity of the construction. Additionally, the level of pretension applied to the bolts can significantly affect the load distribution and overall performance of the joint. Higher pretension may reduce slip and improve load transfer but may also induce higher stresses in the surrounding concrete. Furthermore, the selection of fill materials used to fill gaps within the joint can have profound implications for the structural behavior. Materials such as grouts, epoxies, or elastomeric compounds can alter the load transfer characteristics, damping behavior, and overall integrity of the joint.

By establishing a comprehensive testing program that evaluates these variables under various loading scenarios, both static and dynamic, researchers can gain insights into the performance of these connections. This can help identify optimal design parameters for achieving enhanced strength and ductility, which are essential for resisting the demands of modern construction, particularly in regions susceptible to seismic events. The successful implementation of efficient wall-to-wall joint techniques not only facilitates rapid assembly but also ensures that the overall structural system can withstand the anticipated loads with minimal deformation. Continuous innovation and optimization in connection design are essential for advancing modular construction practices, especially in seismic-prone areas. By refining these techniques and leveraging advanced materials and design methodologies, engineers can achieve enhanced safety, durability, and cost-effectiveness in precast modular buildings, ultimately leading to more resilient built environments.

Efficient slab and beam joint techniques for modular systems

The efficiency of slab and beam joint techniques as shown in Figure 19 is crucial in modular construction, impacting both structural performance and the speed of assembly. Recent advancements in connection designs aim to optimize these joints to achieve higher load-carrying capacities while minimizing the complexity of on-site construction. One effective approach involves the use of precast concrete slabs integrated with either moment-resisting or shear connections to beams, thereby enhancing the overall structural performance of the modular system.

A notable method involves the implementation of dry connections between precast slabs and beams. This system typically utilizes a combination of embedded steel plates and high-strength bolts to create a reliable connection that facilitates rapid assembly. The embedded steel plates are cast into the precast elements, providing a robust interface for load transfer. When high-strength bolts are inserted through the plates, they create a mechanical interlock that enhances shear resistance and overall stability. This connection method minimizes the need for on-site grouting or additional curing, allowing for quicker assembly times and reducing labor costs.

Moreover, the design of these connections must account for the various loading conditions that the modular structures may experience. In scenarios where significant bending moments are present, moment-resisting connections become essential. These connections typically involve the use of welded steel angles or plates that can effectively transfer bending forces between the slab

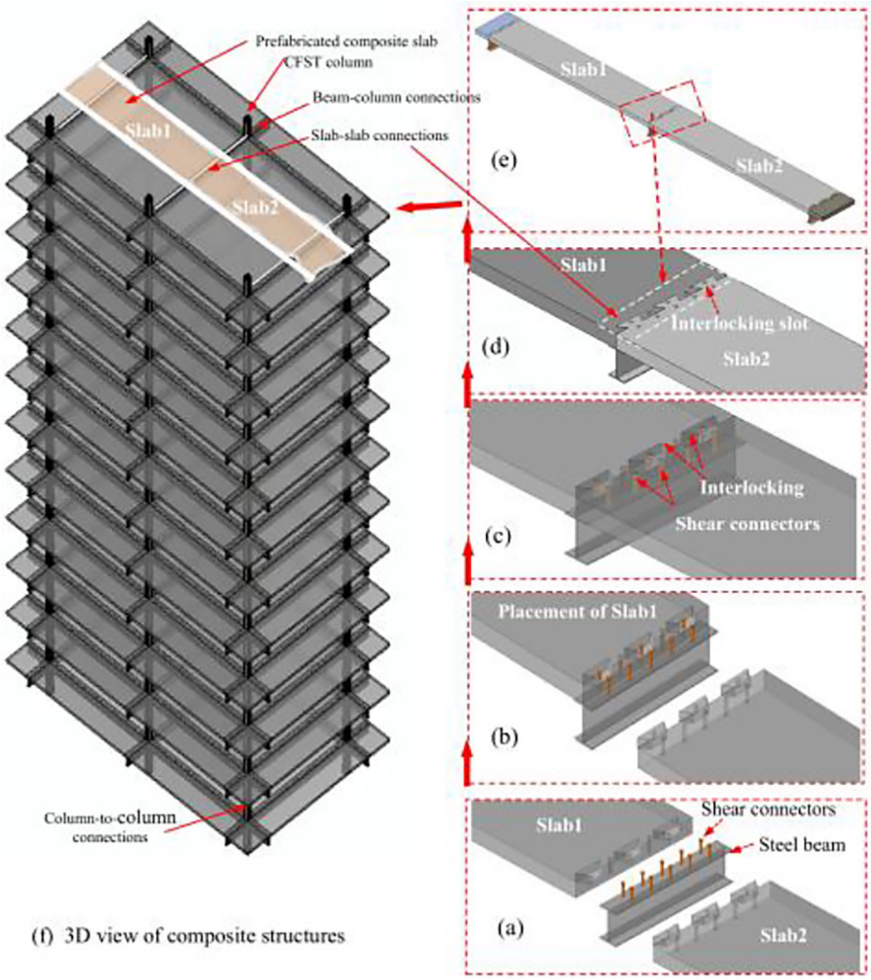

Figure 19. Slab and beam joint techniques [14]

and beam. By ensuring that these connections are designed to accommodate the expected flexural stresses, engineers can enhance the overall stiffness and stability of the modular system, reducing the risk of deformation during service conditions.

In cases where shear forces are more prevalent, employing shear key designs within the joint can provide additional resistance to sliding and rotation. The shear key, typically made from concrete or steel, engages with the beam and slab to transfer lateral forces effectively. This design enhances the overall integrity of the joint and helps maintain alignment between the connected elements, which is especially important in seismic regions where lateral movements can be substantial.

A comprehensive testing program is essential to evaluate the performance of these slab and beam joint techniques under various loading scenarios. Experimental studies should focus on key parameters such as the thickness and material properties of the embedded plates, the level of pretension in the bolts, and the type of shear key employed. Variations in these factors can significantly influence the load distribution and behavior of the connection during both static and dynamic loading conditions.

Additionally, the integration of innovative materials, such as fiber-reinforced polymers or high-performance concrete, can further enhance the performance of slab and beam joints. These materials offer improved strength-to-weight ratios and increased durability, contributing to the longevity of the modular system. The strategic use of such materials can also facilitate lighter and more efficient designs, allowing for larger spans and reduced material usage without compromising safety or performance.

Efficient wall and foundation joint techniques for modular systems

The integration of efficient wall and foundation joint techniques as shown in Figure 20 is

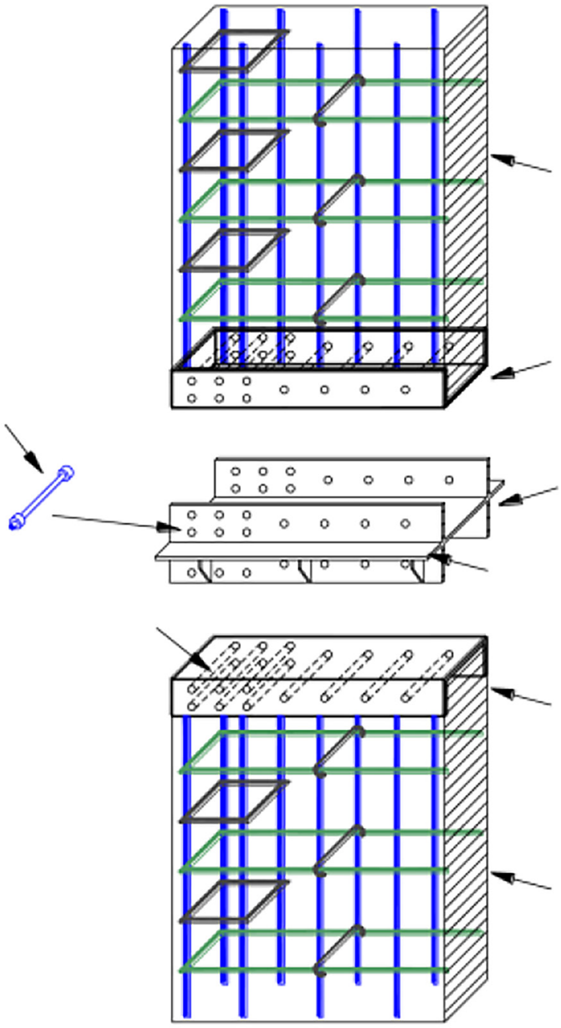

Figure 20. Wall and foundation joint techniques [42]

fundamental in modular construction, as it directly influences the stability, load transfer capabilities, and overall structural integrity of the system. Effective joint designs between precast walls and foundations are essential for ensuring that the modular units behave as a cohesive structure, especially when subjected to vertical loads, lateral forces, and potential seismic activity.

One prevalent approach involves the use of dry connections that incorporate embedded steel plates or brackets within the precast walls and foundation elements. This design allows for the direct transfer of loads between the wall and foundation without the need for wet concrete bonding or curing processes, thereby accelerating the assembly time on-site. The embedded plates, which are cast into the wall units during production, provide a robust interface for bolting the walls to the foundations. When high-strength bolts are employed to connect these plates, they facilitate a secure and rigid joint that can withstand significant shear and tensile forces.

In scenarios where seismic performance is a concern, implementing a shear key or dowel bars within the joint can enhance the shear resistance of the wall-foundation connection. The shear key, typically constructed from reinforced concrete or steel, engages with both the wall and foundation, allowing for effective load distribution and minimizing the risk of lateral displacement during seismic events. Similarly, dowel bars can be strategically placed to ensure proper alignment and to transfer tension and compression forces effectively, contributing to the overall stability of the structure.

Additionally, innovative connection designs, such as the use of post-tensioning systems, can further enhance the performance of wall-foundation joints. In this technique, post-tensioned tendons are incorporated into the joint, allowing for active compression of the wall and foundation elements. This pre-compression helps counteract tensile stresses that may develop during service loads, effectively increasing the load-carrying capacity of the connection and reducing the likelihood of cracking or failure.

Experimental investigations are critical for assessing the performance of these wall and foundation joint techniques under various loading conditions. Key parameters to evaluate include the type and arrangement of embedded steel elements, the dimensions of shear keys or dowel bars, and the level of post-tensioning applied. Through rigorous testing, engineers can determine the optimal configurations that maximize load transfer efficiency while ensuring adequate ductility and energy dissipation during dynamic loading scenarios, such as earthquakes.

Furthermore, the selection of appropriate materials plays a significant role in the performance of wall-foundation connections. Utilizing high-performance concrete or fiber-reinforced composites can enhance the durability and strength of the joint, allowing for greater resistance to environmental factors and extended service life. These materials provide improved tensile and compressive strengths, which are particularly beneficial in mitigating the effects of stress concentrations that can occur at the joint interface.

EVALUATING STRUCTURAL INTEGRITY OF DEMOUNTABLE CONNECTORS: A HOLISTIC APPROACH

The structural integrity of demountable connectors is a cornerstone in ensuring the long-term performance, adaptability, and safety of modular systems. The evaluation process should consider multiple dimensions, such as mechanical strength, flexibility and versatility as represented in in Figure 21. Each of these aspects impacts the system's overall performance under various load conditions, especially when subjected to lateral or cyclic forces typical in seismic or wind scenarios. A holistic evaluation framework allows for a more comprehensive assessment, ensuring that the connectors meet not only strength criteria but also operational efficiency in construction and reuse.

A unified framework for multi-dimensional demountable connection assessment

The performance of demountable connections must be evaluated across several critical parameters, including mechanical metrics (such as strength, stiffness, and ductility), ease of installation, and cost-effectiveness. In modular construction, where rapid assembly and disassembly are key requirements, connectors must provide adequate strength without compromising flexibility. The unified framework proposed for assessing these connections integrates mechanical performance data with constructional efficiency, enabling engineers to assess both short-term structural integrity and long-term sustainability. By considering factors like reusability and ease of replacement, this framework promotes the use of connections that support circular construction principles.

Mechanical metrics redefined: setting new standards for strength and flexibility

Redefining mechanical performance metrics is essential to address the evolving demands of modern modular construction. Traditional measures of strength and stiffness must now be balanced with flexibility and resilience, ensuring that structures can withstand extreme events without permanent deformation or failure.

Shear stiffness optimization for rigidity control

The stiffness of demountable shear connectors can be quantified and evaluated using well-established mechanical principles. For practical design and comparison, the stiffness of a connector is calculated based on load-slip behavior, which is a key indicator of a connector's ability to resist lateral forces without experiencing excessive deformation. According to Eurocode 4 (EC4) guidelines [43], the stiffness at serviceability load $S_{sti,\,test,\,i}$ can be determined using experimental data from cyclic loading tests. The stiffness value is computed as:

$$s_{sti,test,i} = \frac{0.7 \times P_{u,i}}{S_i} \tag{1}$$

where: $P_{u,i}$ represents 70% of the peak ultimate load for the given connector, and S_i denotes the corresponding slip displacement at that load. This equation provides a

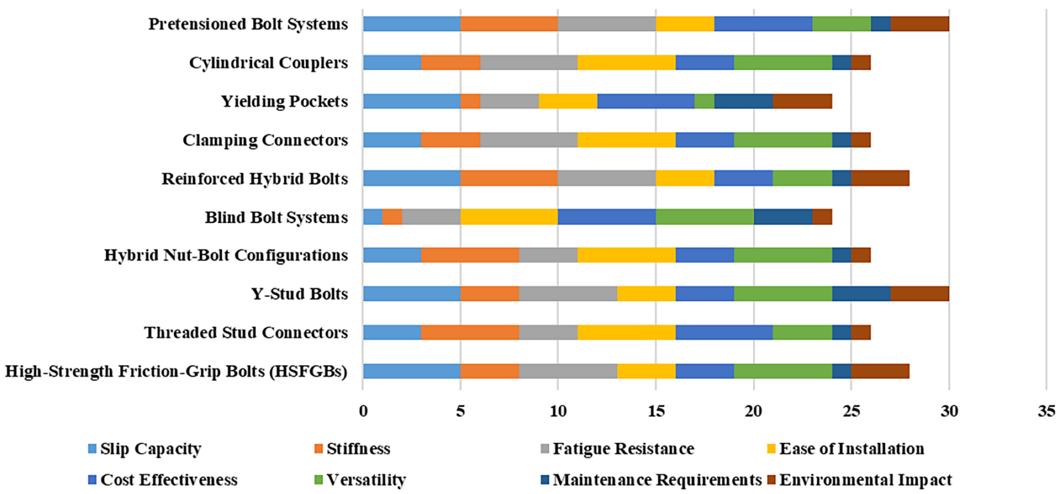

Figure 21. Performance characteristics of connectors

baseline measure of stiffness that reflects the connector's performance under typical service conditions.

In modular systems, achieving optimal shear stiffness is critical to maintaining structural continuity between connected elements. For instance, insufficient shear stiffness can lead to differential displacements between adjacent beams, slabs, or walls, which in turn may cause stress concentrations and cracking at the connection points. By optimizing stiffness, engineers can ensure that the connected components act as a single, cohesive unit, transferring loads efficiently and maintaining structural integrity.

A comparative assessment of different connection systems, such as demountable shear connectors versus welded stud connectors, is often carried out using normalized stiffness values. The relative stiffness score $R_{sti,i}$ for a specific connector is calculated as follows:

$$R_{sti,i} = \frac{S_{sti,bolt\ test,i}}{S_{sti,stud\ test,i}} \quad (2)$$

where: $S_{sti,bolt\ test}$ and $S_{sti,stud\ test}$ are stiffness of tested bolt and stud respectively.

This ratio allows for a direct comparison between the stiffnesses of demountable bolted connections and welded studs, the latter typically serving as a benchmark for stiffness performance. To account for variations across multiple tests and connector types, the relative score is averaged over several samples:

$$R_{sti,j} = \frac{\sum_{i=1}^{ni} Rsti,j}{ni} \quad (3)$$

This average stiffness score provides a more accurate representation of the connector's overall behavior across different loading scenarios.

To further refine the optimization of stiffness, a scaling approach is applied to the relative scores, with the aim of normalizing the stiffness within the range of tested connectors. The scaled score $S_{coSsti,j}$ is given by:

$$S_{coSsti,j} = \frac{R_{sti,j} - R_{sti,jmin}}{R_{sti,jmax} - R_{sti,jmin}} \quad (4)$$

where: $R_{sti,jmin}$ and $R_{sti,jmax}$ are the minimum and maximum relative scores among the tested connectors. This approach ensures that stiffness values are evaluated within a consistent framework, allowing designers to compare different connection types on a uniform basis.

From a structural engineering perspective, optimizing shear stiffness involves a balance between ensuring adequate rigidity to limit deformations and maintaining sufficient flexibility to accommodate load redistributions under extreme conditions. High stiffness is beneficial for controlling deflections and ensuring structural stability, but excessive stiffness can lead to brittle failure modes under seismic or dynamic loading. Therefore, the design of demountable shear connectors must account for both strength and ductility requirements, particularly in systems where the connections are subjected to cyclic or lateral loads, such as in seismic zones.

By systematically optimizing shear stiffness, engineers can improve the overall performance of modular structures, enhancing their ability to resist lateral forces and distribute loads effectively. This not only improves the serviceability and safety of the structure but also extends its lifespan by reducing the likelihood of premature failure at connection points. In modular construction, where rapid assembly and disassembly are key considerations, achieving optimal shear stiffness is crucial for ensuring that the connected elements perform as a single, integrated system capable of withstanding both static and dynamic forces.

Load capacity maximization via enhanced shear strength

Shear strength in demountable connectors is primarily influenced by several factors, including the material properties of the connectors, the design of the joint, and the quality of the assembly. For bolted connections, the bolt diameter, grade, and the quality of the contact surfaces are key parameters that determine the connector's shear resistance. Similarly, for embedded steel plates or dowel-type connectors, the interaction between the concrete and the steel plays a crucial role in defining the load-bearing capacity. The goal of maximizing shear strength is to allow the connector to sustain higher loads without excessive deformation or failure, thus ensuring a robust connection between structural members.

The ultimate load-bearing capacity of demountable connectors can be evaluated through experimental testing and numerical analysis, where load-slip behavior under cyclic or monotonic loading is assessed. For practical purposes, the peak shear strength Pu,i of a connector can be defined as the maximum load it can resist before significant slip occurs, leading to potential separation or failure. Shear strength is typically enhanced through design strategies such as increasing the contact area, improving the surface roughness, and ensuring proper tensioning of bolts. In many cases, the use of high-strength materials, such as Grade 8.8 or 10.9 bolts, or reinforcing steel plates, helps increase the connector's load capacity.

The enhanced shear strength can be calculated using empirical formulas based on the connector type and loading conditions. For instance, for bolted shear connectors, the peak load Pu,i is often determined as:

$$P_{u,i} = A_s \times f_y \tag{5}$$

where: represents A_s the shear area of the connector (bolt or plate), and f_y is the yield strength of the material.

This equation highlights how increasing the connector's cross-sectional area or using materials with higher yield strength can directly improve the load-bearing capacity. The total load-carrying capacity of the connection is then a function of both the connector's shear strength and the number of connectors used in the assembly.

In modular construction, achieving high load capacity is essential for managing the distribution of forces throughout the structure, especially under lateral or seismic loads. For example, in seismic zones, connectors must be designed to resist both static gravity loads and dynamic lateral forces. To enhance shear strength, additional reinforcements, such as embedded steel plates or transverse ties, can be introduced at critical joint locations. These reinforcements help distribute the shear forces more evenly across the joint, reducing stress concentrations and minimizing the risk of failure. Another important aspect of enhancing shear strength is the treatment of the interface between connected components. Proper surface preparation, such as roughening or using bonding agents, improves the frictional resistance at the interface, which contributes to higher shear strength. Additionally, post-tensioning techniques can be employed to increase the normal forces acting on the joint, thereby enhancing the frictional resistance and overall load capacity.

Maximizing load capacity through enhanced shear strength is crucial for ensuring that the modular system can handle both expected service loads and unexpected overload conditions. In practice, this requires careful consideration of material selection, connector design, and installation procedures. For example, in beam-to-column or slab-to-wall joints, the shear strength of the connection must be sufficient to prevent relative displacement between the connected members, which could lead to structural instability or failure. By optimizing the shear strength, engineers can ensure that the modular components behave as a cohesive unit, effectively transferring loads and maintaining the overall stability of the structure.

Ductility: maintaining structural flexibility

Ductility plays a pivotal role in ensuring the resilience of structural connections, particularly in mitigating the effects of dynamic and overload forces. In the context of demountable shear connectors, maintaining sufficient ductility is crucial to prevent brittle failure, which can compromise both safety and seismic performance. From a structural engineering perspective, ductility ensures that the connection can deform under load, absorbing energy without immediate failure, thus providing additional safeguards against unexpected stresses.

In accordance with Eurocode 4 (EC4) [43], which defines the minimum ductility for welded studs as 6 mm, demountable connectors must be evaluated against similar benchmarks to ensure they meet required performance standards. However, unlike welded studs, demountable connections often experience variabilities in slip due to their disassembly nature, making precise control over ductility more challenging. Therefore, new formulations can be proposed to measure ductility, taking into account the slip response and ultimate load-bearing capacity under cyclic or sustained loads.

The novel approach to enhancing ductility in demountable connectors could involve reinforcing the connector with hybrid materials or integrating pre-stressed elements that improve post-yield behavior. By extending the deformation range before reaching ultimate strength, as shown in modified versions of Eurocode 4's ductility formulas, we can redefine the ductility ratio for these systems:

$$\mathrm{R_{Ducti}} = \frac{Duct_{demountable,i}}{Duct_{stud}} \tag{6}$$

$$R_{Ductj} = \frac{\sum_{i=1}^{n} R_{Ducti}}{n} \tag{7}$$

$$Sco_{Ductj} = \frac{R_{Ductj} - R_{Ductjmin}}{R_{Ductjmax} - R_{Ductjmin}} \tag{8}$$

where: $Duct_{demountable,\ i}$ represents the slip corresponding to the ultimate strength for demountable connectors, and $Duct_{stud}$ remains the standard ductility for welded studs. This assessment framework incorporates material flexibility and energy absorption capacity, emphasizing the importance of optimizing slip performance in demountable systems to prevent brittle behavior.

Design for efficiency: Assembly and disassembly in modern construction

This approach emphasizes the optimization of both assembly and disassembly processes to enhance productivity, reduce waste, and promote sustainability. The development of demountable connection mechanisms is central to this design philosophy, as it enables quick, efficient, and safe construction while facilitating future alterations or relocations.

Design for assembly: Efficiency in construction

The shift towards sustainable construction practices necessitates a transformative approach to design, particularly in the realm of demountable connectors. Design for Disassembly (DfD) is emerging as a crucial methodology that not only enhances the reusability of building components but also contributes to a circular economy within the construction industry. At the heart of effective DfD is the principle of accessibility, which dictates the ease with which connectors can be assembled and disassembled. Innovative connector designs that incorporate self-aligning features and intuitive release mechanisms can significantly reduce manual intervention and installation time. For instance, connectors utilizing magnetic or automated engagement systems could minimize the need for specialized tools, thereby streamlining the disassembly process while maintaining structural integrity.

Moreover, the materials chosen for connectors play a pivotal role in their sustainability and performance. By exploring advanced materials such as high-strength polymers or eco-friendly alloys, designers can create connectors that not only resist corrosion and fatigue but also possess lightweight properties that facilitate easier handling during disassembly. This strategic material selection can enhance the overall lifecycle of connectors, allowing them to endure multiple disassembly and reassembly cycles without loss of performance.

Incorporating digital technologies into the design process further amplifies the efficiency of disassembly. The use of building information modeling (BIM) can provide detailed insights into connector specifications, spatial configurations, and loading conditions throughout a structure's lifecycle. This enables engineers to optimize connector layouts for disassembly, ensuring that components can be removed in a predetermined sequence that safeguards adjacent structures and reduces damage.

To quantitatively assess the efficacy of disassembly strategies, a novel design for disassembly (DfD) score can be established, taking into account factors such as connector accessibility, material sustainability, and reusability potential. The scoring framework may be represented by the following equations:

$$ScoD = \begin{cases} 1, if\ disassembly\ requirements\ are\ met \\ 2, if\ disassembly\ requirements\ not\ met \end{cases} \tag{9}$$

$$ScoNCF, j = \frac{1}{Nj} \times \frac{Nj}{Njmin} \times \frac{Njmax}{Njmin}$$

In these equations, ScoD reflects the overall disassembly score, while ScoNCF,j quantifies the fitting efficiency of each connector. The parameters N_j , N_{jmin} , and N_{jmax} define the actual fitting, minimum fitting requirement, and maximum fitting capacity, respectively.

By leveraging this refined approach, we ensure that demountable connectors maintain structural flexibility, critical in scenarios where they are subjected to seismic loads or repeated dynamic forces. This not only extends the service life of the structure but also enhances its adaptability in modular and demountable applications.

Design for disassembly: Enabling reusability and sustainability

By implementing DfD principles, structures can be designed for efficient assembly and disassembly, which minimizes waste and lowers lifecycle costs. Key strategies include utilizing modular connection systems that allow for straightforward assembly on-site and employing mechanical fasteners such as high-strength bolts (HSB) that facilitate rapid disconnection without compromising structural integrity.

The reusability of demountable connections is significantly influenced by material selection and connector design. High-durability materials like stainless steel ensure that connections maintain performance through multiple assembly cycles.

Additionally, designing connectors to allow easy disassembly, such as slip-critical connections that enhance load transfer while remaining easily removable, promotes long-term reuse.

The sustainability benefits of demountable connections can be quantified through metrics such as embodied energy (EE) and waste reduction. Embodied energy can be calculated using the formula:

$$\mathrm{EE} = \sum(W \times E) \qquad (10)$$

where: W – weight of material, E – energy required for production.

This approach highlights how DfD can reduce construction waste significantly, with studies indicating reductions of up to 60% compared to traditional construction methods.

Evaluating the efficiency of demountable connections involves several performance indicators. The accessibility score (AS) assesses how easily connectors can be accessed for disassembly, while the reusability index (RI) quantifies the potential for components to be reused in future projects. The disassembly time (DT) measures the time required for disassembly, providing insights into overall efficiency and labor costs. These metrics can be expressed as:

$$AS = \frac{(Number\ of\ Accessible\ Connectors)}{(Total\ Connectors)} \times 100 \qquad (11)$$

$$RI = \frac{(Number\ of\ Reusable\ Components)}{(Total\ Connectors)} \times 100 \qquad (12)$$

$$DT = \sum(Time\ Required\ for\ Each\ Connector) \qquad (13)$$

Future innovations in demountable connections are expected to enhance DfD practices further. Integrating smart technologies, such as structural health monitoring sensors, will provide valuable data for planning disassembly while ensuring safety. Moreover, advancements in connection technologies, including self-aligning systems, will improve the overall performance and longevity of demountable connections.

Future trends in reconfigurable and demountable connection systems

The demand for adaptable and sustainable construction practices has led to significant advancements in reconfigurable and demountable connection systems. These innovative solutions enable structures to be efficiently assembled, disassembled, and reconfigured, responding to evolving architectural needs while minimizing waste and environmental impact. The following sections delve into specific trends that are shaping the future of demountable connections, focusing on enhancing structural performance and operational flexibility.

Redefining beam-column joint flexibility for future buildings

Future trends in demountable beam-column joint systems will emphasize the integration of advanced materials and design methodologies to enhance joint flexibility. Innovative connection designs will utilize high-strength, lightweight steel plates coupled with adjustable tensioning systems that allow for precise alignment during construction. This approach will not only facilitate rapid assembly and disassembly but will also allow for dynamic adjustments to accommodate differential movement during seismic events. The incorporation of smart technologies, such as sensors embedded within the joints to monitor load distribution and deformation in real-time, will enhance the understanding of joint performance and allow for proactive adjustments and maintenance, ultimately leading to more resilient structures.

High-performance wall-to-wall and column-to-column demountable connections

In the realm of wall-to-wall and column-to-column connections, future developments will focus on enhanced load transfer mechanisms that leverage post-tensioned connections with specialized couplers designed to facilitate easy disassembly while maintaining structural integrity. The use of modular wall systems that incorporate integrated shear keys will ensure effective load distribution, while advanced anchoring systems will allow for rapid reconfiguration without compromising performance. Additionally, research into hybrid connection systems that combine traditional concrete with innovative materials such as fiber-reinforced polymers will reduce weight while enhancing strength. These advancements will promote faster construction times and greater adaptability in response to evolving design requirements.

Table 2. Challenges and limitations of shear connectors

Connector type	Challenges	Limitations	Potential solutions
High-strength friction-grip bolts (HSFGBs)	Complex installation process	Requires precise torque control	Develop torque monitoring systems
Threaded stud connectors	Susceptible to corrosion	Limited fatigue life	Use corrosion-resistant materials
Y-stud bolts	Difficulties in alignment during installation	Higher cost compared to standard connectors	Standardize installation procedures
Hybrid nut-bolt configurations	Potential for nut loosening over time	Requires periodic maintenance	Implement locking mechanisms
Blind bolt systems	Limited slip capacity	Potential issues in load transfer	Explore hybrid designs for improved performance
Reinforced hybrid bolts	Increased complexity in design	Higher fabrication costs	Streamline manufacturing processes
Clamping connectors	Limited load transfer capacity	Not suitable for high-load applications	Optimize design for enhanced performance
Yielding pockets	May compromise overall stiffness	Requires careful design to avoid excessive yielding	Utilize advanced materials for strength
Cylindrical couplers	Limited research on long-term performance	Not widely adopted in practice	Conduct long-term performance studies
Pretensioned bolt systems	Complexity in installation	Requires specialized tools	Simplify installation process

Next-gen foundation connections for structural stability

Future trends in foundation connections will concentrate on developing reconfigurable systems that enhance stability while allowing for easy assembly and disassembly. Demountable foundation connections may incorporate innovative bearing pads made of elastomeric materials that provide flexibility to accommodate settlement and dynamic loading conditions, improving overall foundation performance. Additionally, the integration of smart foundation technologies, including advanced sensors that monitor ground movement and load conditions, will enable real-time data collection and analysis, allowing for timely interventions. Future designs may also explore the use of precast concrete components with built-in connection systems that facilitate rapid installation and ensure a robust foundation capable of supporting varying structural loads efficiently.

Beam-slab demountable joints: Towards smarter construction

In beam-slab joint systems, the future will see the adoption of self-adjusting demountable connections that utilize innovative mechanical fasteners, such as cam-lock or wedge systems, which provide secure locking without the need for extensive tooling during disassembly. These systems will allow for easy reconfiguration of spaces, catering to changing usage requirements without compromising structural performance. Enhanced beam-slab connections will also integrate smart monitoring technologies that utilize IoT devices to track joint performance metrics over time, ensuring safety and reliability. Furthermore, the use of automated construction methods, including robotics for installation and adjustment of beam-slab connections, will streamline construction processes, reduce labor costs, and minimize human error, leading to a more efficient and sustainable construction industry. Table 2 summarizes the key challenges and limitations associated with various connector types used in modular and composite construction systems. Understanding these factors is crucial for optimizing performance and enhancing the reliability of connection mechanisms in structural applications.

CONCLUSIONS

This review has synthesized the current state of demountable connection systems, elucidating their pivotal role in advancing sustainable construction practices through reusability and adaptability. The following key insights are derived from the analysis.

Demountable connections have been categorized based on geometric configurations, such as bolted connections with and without embedded nuts, tapered couplers, and unique connector designs. Each configuration presents a distinct balance of mechanical performance characteristics, such as stiffness and ductility. For example, connectors that utilize tapered couplers not only ensure superior force transfer under loading conditions but also enhance the ease of disassembly, enabling efficient reuse of structural elements. In contrast, connections lacking embedded nuts provide straightforward disassembly but may sacrifice overall stability in high-stress scenarios. This trade-off necessitates a design approach that prioritizes performance metrics aligned with specific structural requirements.

The classification of demountable connections enables engineers to select appropriate systems based on project-specific needs. For instance, tapered couplers are advantageous in applications where rapid assembly and disassembly are required, such as modular and prefabricated structures. Meanwhile, simpler bolted connections without embedded nuts may be suitable for temporary structures where ease of dismantling outweighs long-term stability concerns. This categorization also assists in retrofitting existing structures, allowing engineers to choose connections that best balance structural performance and disassembly efficiency for future reuse or modification.

Recent advancements have focused on optimizing shear performance through innovative design solutions that mitigate premature shear failure. The development of LN and SYD connectors exemplifies a forward-thinking approach to address challenges related to bolt hole tolerances and shear stiffness. By strategically incorporating features that enhance ductility while maintaining adequate strength, these connectors illustrate the importance of a balanced mechanical response. For instance, integrating tapered couplers with advanced materials such as high-strength steel can improve energy dissipation capabilities, crucial for applications in seismic regions. The integration of performance data from experimental studies provides valuable insights for refining connector designs, ensuring they meet the evolving demands of contemporary structural applications.

Implementing advanced connectors like LN and SYD enhances the safety and performance of structures in seismic zones. Engineers can use these innovations to design buildings that are not only resilient against lateral forces but also capable of withstanding repeated loading without significant degradation. This improves the lifecycle performance of structures, reducing maintenance and retrofitting costs. Furthermore, by addressing bolt hole tolerances and enhancing shear stiffness, these advanced connectors facilitate precise assembly in the field, reducing construction errors and improving overall build quality.

A robust evaluation framework has been introduced, integrating mechanical, constructional, manufacturing, and economic performance metrics. This systematic approach facilitates the quantification of demountable connection's efficacy, enabling engineers to make informed design choices. The ability to adjust weight values in the evaluation allows for customization based on project-specific requirements, underscoring the adaptability of demountable systems in diverse construction contexts. This versatility is crucial in addressing varying structural demands, from high-rise buildings to modular construction.

The comprehensive evaluation framework aids decision-making by providing a quantifiable basis for selecting connection systems. Construction professionals can leverage this tool to balance performance with cost, ensuring optimal solutions for specific applications, such as selecting the most efficient connectors for high-rise buildings or temporary structures. Additionally, this framework supports the assessment of long-term sustainability by quantifying the environmental and economic impacts of reusable connection systems, aiding regulatory compliance and sustainable certification processes.

The future trajectory of demountable connection systems is intrinsically linked to the integration of advanced materials and design philosophies. The incorporation of smart materials, such as shape memory alloys (SMAs), offers transformative potential for enhancing structural resilience and performance under dynamic loads, including seismic events. SMAs can provide passive damage control mechanisms, enabling structures to recover from extreme loading while maintaining operational integrity. Additionally, the utilization of hybrid systems that combine traditional materials with fiber-reinforced polymers (FRPs) can further augment the strength and durability of demountable connections. Furthermore, exploring alternative assembly methods, such as utilizing precast components and robotic fabrication, can streamline construction processes and improve the overall efficiency of connector assembly and disassembly.

The adoption of advanced materials and digital technologies enables more resilient, efficient, and adaptable construction practices. Incorporating SMAs and hybrid systems can extend the lifespan and functionality of structures, while BIM and simulation tools offer improved accuracy in design and project coordination. This fosters better resource management and reduces construction time, aligning with sustainable and future-oriented building practices. Furthermore, the use of robotic fabrication enhances construction speed and accuracy, reducing labor costs and minimizing human error, while improving safety during the assembly and disassembly of structural systems.

Moreover, the increasing emphasis on digital technologies, including BIM and advanced simulation tools, presents opportunities for optimizing the design and performance evaluation of demountable connections. These technologies facilitate precise modeling of connection behavior under various loading scenarios, leading to improved design solutions and enhanced collaboration among stakeholders throughout the construction process.

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