Experimental investigations to identify challenges in design of prefabricated concrete structures for disassembly and reuse

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Abstract

The Norwegian Sirkbygg project investigates the design for disassembly of prefabricated concrete components as a strategy to reduce the environmental impact of constructions. In the project, a mock-up of a building structure was constructed and disassembled with the objective to identify challenges for component reuse. Emphasis is placed on the design of connections for hollow-core slabs. The study investigates the use of adhesion-reducing agents as a technically and economically feasible method to facilitate the disassembly and reconditioning of such slabs, maintaining the advantages of wet-joints for force transfer and diaphragm action while avoiding fundamental changes to current production and construction processes.

1 Introduction

Concrete is the most-used material in construction, consuming vast natural resources and contributing about 7% of global carbon emissions [1]. Circular strategies, such as design for disassembly (DfD) and reuse of durable prefabricated concrete components, can mitigate these impacts [2], [3], [4], [5], [6]. Since the 1980s, pioneering multistory projects in Germany, Sweden, and the Netherlands have successfully reused precast concrete panels [7]. More recently, Norwegian projects have demonstrated the feasibility of reusing precast hollow-core slabs (HCS) in multistory buildings [8], [9], [10].

Despite these successes, large-scale, cost-effective reuse of prefabricated concrete components requires further research. A major challenge is designing connections that facilitate disassembly and reintegration. Slab connections, in particular, remain almost underexplored [11]. Proposed solutions include dry connections, such as steel diaphragms for HCS-wall joints [12], beam-slab connections in seismic regions [13], and half-lap joints with steel plates and bolts [11]. However, high adaptation costs, and uncertain long-term benefits, still limit widespread adoption [14]. Additionally, technical challenges, such as large construction tolerances in concrete, may further limit the implementation of new dry joint concepts.

Meanwhile, wet joints—commonly used for precast slabs—need modifications to improve disassembly. Available studies addressing this topic are scarce, however. Halding suggested using low-strength grouting mortars to reduce adhesion [15], but this approach has drawbacks as discussed further down in the paper. Alternatively, adhesion-reducing agents applied to HCS joint surfaces have been proposed to ease disassembly [16].

Building on the latter approach, this paper presents an experimental study of a full-scale mock-up of a precast concrete structure, conducted in the framework of the Norwegian SirkBygg project [17]. The paper focusses on the connections of HCS, with emphasis on the longitudinal joint between the slabs. Section 2 examines longitudinal joint design, balancing horizontal shear transfer and disassembly needs. Section 3 describes the conducted experimental study, while Section 4 discusses the results and identifies future pathways for improving DfD procedures. Conclusions are summarized in Section 5.

2 Considerations and experience on the Dfd of longitudinal HCS joints

2.1 Shear force transfer in persistent design situations

This section outlines the purpose and design of longitudinal joints between HCS, focusing on disassembly and reuse. Only systems without a concrete topping are considered, as its removal is costly and time-consuming. While studies suggest reuse with the topping is possible, it increases self-weight, imposing design constraints such as higher column load demands and reduced floor heights [10], [14].

One of the primary functions of the longitudinal joint between HCS is to ensure structural continuity by enabling in-plane force transfer through diaphragm action. Their design follows shear friction theory, where shear resistance arises from three main contributions:

1. Adhesion between the joint grout and the structural element.
2. Normal stress on the joint.
3. Reinforcement crossing the joint.

Adhesion increases with grouting concrete strength, as observed in early tests by Reinhard [18]. However, grouted joints in precast floors are typically assumed to crack in service due to restraint forces. Even if some remain intact, shear resistance is generally attributed to friction alone [18], [19], driven by normal stress and reinforcement across the joint. The upper shear resistance limit is defined by the compression strut capacity. For a detailed discussion of failure mechanisms and design rules, see [18], [19].

2.2 Influence of adhesion between grout and HCS on the disassembly process

Disassembling HCS requires breaking both longitudinal and transverse joints, but adhesion between joint grout and HCS surfaces poses a challenge. Though not considered in joint design for horizontal shear (section 2.1), this adhesion can hinder disassembly and cleaning, increasing time and cost [16]. For instance, Fig. 1 (left) shows an HCS from Volda's swimming hall (Norway), installed in autumn 2023 and dismantled months later. The joint, cast with common Norwegian joint concrete mix for winter season casting of quality C35/45 and d_{max}=8mm at +5°C, proved extremely difficult to remove even with a powerful chisel hammer, taking ~15 minutes per meter and causing slab damage [20]. Conversely, in other Norwegian [16], and Dutch [14], pilot projects, grout removal was significantly easier. In a Lysaker (Norway) building from the 1980s, after cutting the transverse support edge with a diamond saw, the grout detached easily. To prevent collapse, detached slabs were supported by trestles before crane removal (Fig. 1 (right)) [16], [20].

Fig. 1: Difficult removal of grouting concrete from HCS recovered from the swimming hall in Volda (Norway) (left); Right: Lifting of a HCS from a building in Lysaker (Norway) after breaking of grouting concrete with a jackhammer inducing detachment from adjacent slab (right).

Variations in execution quality over time likely explain the differing adhesion observations. Before the 1990s, dry, fast-setting grout often left joints partially filled, whereas modern superplasticizers ensure highly flowable concrete, controlled curing, and pre-wetting minimizes absorption. Improved frost protection, including antifreeze additives, has further enhanced grout quality and adhesion to HCS surfaces [16], [20].

These factors underscore the need for further research on adhesion forces in HCS disassembly and the development of efficient, repeatable methods. The Sirkbygg project explored adhesion-reducing agents on HCS surfaces, an approach previously shown to improve disassembly potential [16].

3 Sirkbygg mock-up

3.1 Layout and main components

A full-scale mock-up was constructed and disassembled at *Spenncon*'s premises in Hønefoss (Norway) to study the disassembly and reuse challenges of prefabricated concrete components. The structure adhered to Norwegian Building Standards, which align with Eurocodes, and used standard precast components with minor adaptations in execution practices. Fig. 2 shows the structure's layout, with HCS spanning two bays. Vertical loads are transferred to the foundation by columns and two walls at axes 3 and A. The overall stability is provided by the HCS diaphragm, which transfers horizontal forces to these walls and to the previously existing moment-resisting columns at axes 1C and 2C. The paper will focus on the HCS and their connections (both between slabs and to supporting beams and walls).

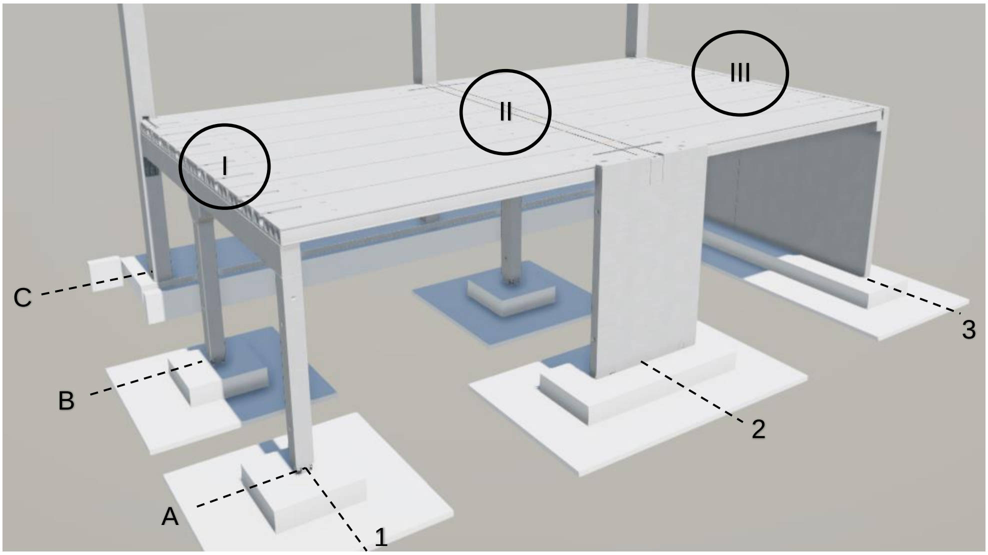

Fig. 2: Model of the mock-up [20].

3.2 Connections

The mock-up includes various connections between HCS and adjacent elements. In axis 1, the HCS are supported by a rectangular beam (connection I) with a bolted connection using a threaded sleeve. In axis 2, the HCS are supported by an inverse T-beam (ITB) (connection II, see also Fig. 3 (left)), while in axis 3, a wall nib provides support to the HCS (connection III, Fig. 3 (right)). Reinforcing bars are placed in the longitudinal joints between the HCS, crossing connection II to provide continuous tying of the floor system. In connection III, threaded rods are embedded in the foreseen slots on the topside of the HCS, enabling force transfer to the wall. Beams and walls in axis 1, 2 and 3 are connected using welded steel plates acting as continuous ties crossing the longitudinal joints of the HCS.

Disassembly requires cutting through the reinforcing bars, threaded rods, and grouting concrete along the red lines in Fig. 3. Since removing the grouting concrete from the concrete filled slot is time-intensive, the cut-off threaded rod remains, and a new slot must be cut for reuse (Fig. 3 right). The existing threaded sleeve in the wall can be reused unless geometrical incompatibility arises. In this case, one solution is to produce a new sleeve in the wall, matching the location of the embedded rods in the HCIS.

To prevent damage during cutting, an 80 mm wide foam strip is placed between the HCS and supporting beam/wall before casting (Fig. 3 left). The foam also prevents the grouting concrete from adhering to the flange or wall nib. Adhesion-reducing agents are applied before casting to the ITB flange, walls (both in axes A and 3), and longitudinal side faces of the HCS to lower adhesion forces and ease disassembly (section 3.3).

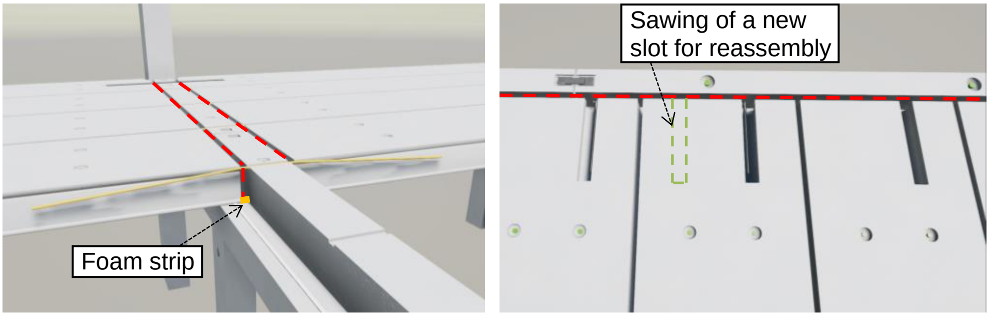

Fig. 3 Joint between HCS and ITB (connection II) (left) and between HCS and wall nib (connection III) (right) [20].

3.3 Adhesion-lowering agents

Seven adhesion-reducing products developed by Master Builders Solutions were investigated in this study, with their development and selection based on the results of a prior study by Myhr Lamvik and Jensen [16]. The products were applied to the longitudinal side surfaces of the different HCS (Fig. 4 (left)), the surfaces of the supporting walls and the ITB in contact with the short end of the HCS (Fig. 4 (right)), as well as to the bottom surface of columns and walls in contact with the foundations. Some of these surfaces were left untreated as reference areas.

All tested products were low-viscosity liquids applied using a pressure sprayer with nozzles designed for each product. The sprayer and nozzles were provided by *Master Builders Solutions*, and their technicians performed the application on the concrete elements. The work was conducted under a roof on dry concrete surfaces, with each surface treated with two thin layers of the adhesion-reducing product. The sprayer ensured an even mist of fine droplets, and the application was performed under dry weather. After application, the products dried on the concrete surface for approximately 15 minutes before being stored for 5 days until assembly.

Fig. 4 Application of the adhesion-reducing products on lateral surfaces of the HCS (left) and the web of the ITB (right). Zones marked with a X specify the reference areas without products.

3.4 Assembly

The test construction was assembled between August 20 and 23 in 2024 by two workers assisted by a mobile crane. Fig. 5 (left) depicts the placing of one of the HCS by means of the crane. The detail of the foam strip on top of the wall nib supporting the HCS in axis C is highlighted in Fig. 5 (right).

For the grouting of the HCS joints and slots, a commonly used C30 concrete mix for summer season joint casting in Norway was used. Grouting was carried out in humid, cloudy weather conditions. Therefore, no pre-watering was done before grouting.

Fig. 5 Placing of a HCS with the mobile crane (left) and foam strips on top of wall nib supporting the HCS in axis C before grouting (right).

3.5 Disassembly

The mock-up disassembly took place between September 23 and 25, 2024, with a minimum four-week interval after assembly to ensure the joint concrete reached its 28-day strength. Disassembly began with saw cutting the end connections to wall nibs (connection III) and ITB (connection II), down to the foam plastic strip (Fig. 3, Fig. 5). The worker noted that reaching the foam strip made it easy to cut to the correct depth, while cutting through reinforcement bars and threaded rods required more force but was still manageable.

The connection between HCS and the rectangular beam (connection I) was disassembled by unscrewing the bolt from the threaded sleeve using -a battery-powered impact wrench. After cutting the end joints and removing the bolts, the HCS were lifted with a crane using embedded anchors. To facilitate disconnection of the longitudinal joints, a bending moment was induced by shortening the lifting chains on one side (Fig. 6 (left)). However, in several cases, this procedure resulted in insufficient tensile stress in the joint, causing the first crack to appear in the joint between the adjacent pair of HCS, rather than in the joint closest to the slab being dismantled, as originally planned, see Fig. 6 (left). To address this, shallow saw cuts were made in this joint, and wedges were inserted into these cuts to initiate cracking by means of sledgehammer hits before lifting the slabs with the crane, see Fig. 6 (right).

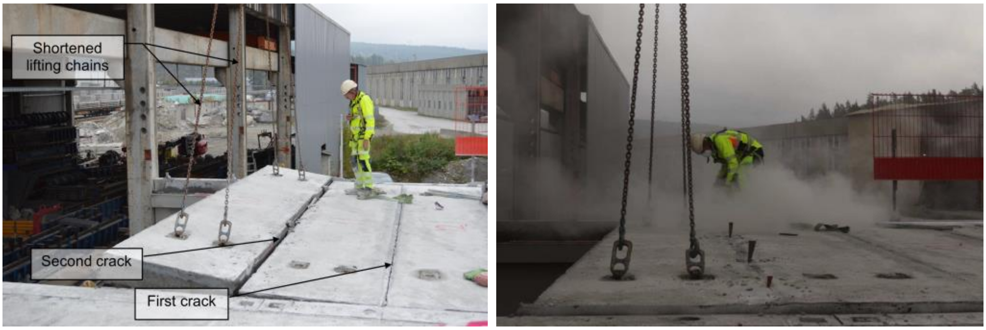

Fig. 6 Inducing detachment of the longituidnal joint by means of adjusted lifting chains (left) and placing of wedges into saw cuts to induce cracking (right).

3.6 Reconditioning

For reuse, the reclaimed concrete components required refurbishment, primarily the removal of grouting concrete from the HCS edges, ITB web, and wall nib.

Joint concrete on the HCS long sides was removed with a battery-powered chisel hammer. Surfaces treated with adhesion-reducing products (section 3.3) allowed easy removal, while untreated areas required significantly more time and effort. Treated surfaces took 60–85 seconds per meter, whereas untreated ones required 200–350 seconds. Fig. 7 (left) shows chiseling in a treated area, where a longitudinal crack formed, detaching the concrete in large sheets. Only one of the seven tested products showed noticeably higher adhesion, while variations among the others were minor, likely due to differences in grout quality, water addition, worker experience, and worker posture during removal.

Fig. 7 Removal of grouting concrete from the longitidinal side of a HCS, where adhesion-reducing products were applied (left) and from a reference area at the short end of the HCS (right).

Short sides of the HCS were untreated, assuming easy removal due to smooth sawn surfaces and low adhesion of plastic plugs covering the hollow cores of the slabs. However, removal was more labor-intensive than expected (Fig. 7 (right)).

Residual grout on the beam's side edges detached easily during disassembly, with any remaining material removed effortlessly with a chipping hammer, regardless of adhesion-reducing agents. In contrast, grout on the vertical wall section above the nib had higher adhesion but was easily removed where adhesion-reducing products were applied.

Besides concrete removal, new end slots were cut into the HCS to enable connections to the wall nib (Fig. 3 (right)). Additionally, welding remainders on the embedded steel plates in the beams (section 3.2), previously cut during disassembly, were removed using an angle grinder.

4 Lessons learned and envisaged improvements

4.1 Longitudinal joints

In traditional HCS longitudinal joint designs, adhesion forces are typically neglected when assessing horizontal shear resistance, assuming joints are cracked (Section 2.1). Cracking results from temperature variations, shrinkage, and external loading during service life. Shear forces will concentrate in elements that provide stiffness and resistance to horizontal loads, such as shear walls or cores, where significant cracking in the joints is more likely. However, structures that are being disassembled for reuse, have most likely been subjected to load intensities far below the ultimate load capacity. Hence, adhesion performance of the HCS longitudinal joints is likely to strongly vary within a building. In areas with less pronounced cracking, adhesion can still oppose significant resistance to the action effects introduced during disassembly, as evidenced in the Sirkbygg Mockup (section 3.5).

While adhesion-reducing agents proved highly effective during cleaning (Section 3.6), joint design can be further optimized. Specifically, the joint should be designed so that the maximum tensile stress, σ_{max}, induced by crane force $F_{max,}$ applied with eccentricity Δ, exceeds the joint's adhesion capacity with a specific target probability (Joint 1, Fig. 8). This approach will prevent uncontrolled cracking, (e.g., in Joint 2, Fig. 8), as shown in Fig. 6 (left)), and reduce the need for additional separation measures like sawing, wedge insertion, and hammering (Fig. 6 (right)), keeping them as efficient backup solutions.

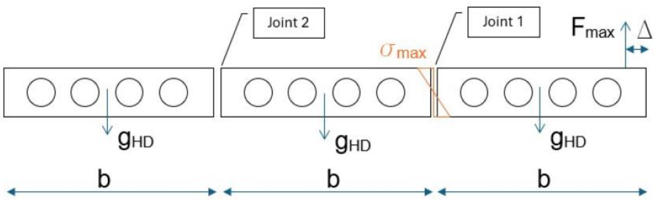

Fig. 8 Stress induced in the longitudinal joint of the HCS when submitted to a lifting force F_{cr} induced by the crane.

An alternative to crane-induced lifting for disassembly, as used in the Sirkbygg mock-up, is applying an uplift force from below. As shown in Fig. 9, a remote-controlled jacking device placed under the joint would induce tensile stress in the upper chord of the HCS, rather than the lower chord as in the crane method (Fig. 8). Despite this difference, joint design optimization with adhesion-lowering agents follows the same principles.

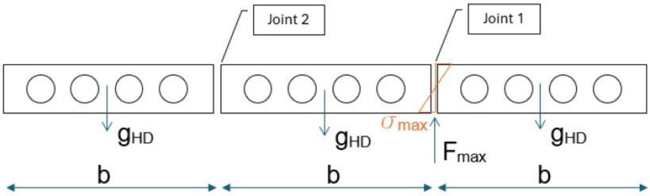

Fig. 9 Stress induced in the longitudinal joint between HCS when inducing an uplift force for lifting the slab.

The primary improvement in joint design should focus on optimizing adhesion-reducing agents. Master Builders Solutions is currently conducting pull-off tests to assess the adhesion performance of various products. Preliminary results indicate that untreated samples exhibit 5–12 times higher adhesion resistance than treated ones. Further analysis will be the subject of future studies.

Additionally, optimizing the grouting concrete quality could enhance the DfD properties of the joint, though this presents challenges. Lower-strength concrete may reduce adhesion resistance, as explored by Halding [15], but several factors limit its feasibility. Frost resistance requirements, for instance, mandate in Norway a minimum strength class of C35 for casting below 5°C and C30 above [21]. The joint must also withstand vertical shear forces. Furthermore, practical considerations require using the same concrete for longitudinal joints and adjacent connections, such as e.g. floor-wall joints, for which low-strength mortars would be unsuitable. Moreover, grouting concrete tensile strength is crucial for anchoring reinforcement in longitudinal joints and HCS channel slits, ensuring diaphragm action and structural robustness. It also contributes to shear capacity when HCS cores are concrete-filled, as outlined in Annex F of EN 1168 [22].

Given these constraints, adhesion-reducing measures offer a technically and economically viable solution for DfD in HCS longitudinal joints. According to prEN 1992-1-1 [23], the extruded surfaces of such joints can be classified as “smooth”.

Future studies on joint improvements should include shear-off tests, expanding on the results in [16]. These tests should verify that adhesion-reducing products do not significantly affect the friction coefficient by altering surface roughness or interlocking between HCS and grouting concrete. Additionally, building on earlier studies [18], [24], tests could assess whether surface indents counteract potential shear capacity loss without hindering disassembly.

4.2 End connections

The observations from grouting concrete removal remainders on the contact surfaces of the connections between the HCS and their supporting beams or walls suggest distinguishing the use of the adhesion-lowering products depending on the surface type:

Free concrete surfaces left untreated after compaction (e.g., the wall above the nib supporting the HCS) seem to require adhesion-reducing measures to ease concrete removal after disassembly. These surfaces can be classified as “smooth” or “rough” per prEN 1992-1-1 [23]. Conversely, concrete cast against smooth formwork (e.g., the ITB side edge in contact with the HCS) does not require adhesion-reducing measures for effective joint concrete removal. These surfaces can be classified as “very smooth” per prEN 1992-1-1 [23].

Principally, adhesion-reducing agents could be applied as well to the short ends of the HCS to address the challenges in concrete removal (Fig. 7, right). However, applying these products to the slab ends poses a risk of unintentional overspray into the slit, which is undesirable, as adhesion within the slit is essential. To circumvent such problems, saw cutting of the end connections (Fig. 3) should be performed at the interface between the HCS and the grouting concrete.

5 Conclusions

The concrete industry is in need to reduce its environmental footprint. Reuse of prefabricated components is an efficient strategy to this end. A fundamental issue when it comes to component reuse is connection design and detailing. Existing studies mainly focus on dry connections (e.g. bolted connections), suggesting that wet connections relying on grouting of joints are not suited for Dfd and reuse. The study presented in this paper proves the contrary. We present an effective solution for the design and disassembly of joints for widely used hollow-core slabs (HCS), with focus on the longitudinal joints between slabs. From the conducted study it can be concluded that:

- Adhesion forces in HCS joints of structures built nowadays can oppose significant resistance to the disassembly and reconditioning of the HCS.
- The use of adhesion-reducing agents provides a technically and economically feasible solution to this, maintaining the advantages of wet joints for assuring constructability with regards to construction tolerances, force transfer and diaphragm action, thereby avoiding fundamental changes to current production and construction processes.
- The use of adhesion-reducing agents is considered advantageous with respect to the use of low-strength mortars, which faces several limitations.
- Such agents are recommended for use on joint surfaces that can be classified as “smooth” or “rough” according to prEN 1992-1-1 [23]. Surfaces classified as “very smooth” do most likely not require adhesion-reducing measures for the effective removal of the joint concrete.
- To overcome the adhesion resistance, it is possible to induce controlled stresses in the grouting concrete by lifting the slabs with a crane or a jacking device, enabling efficient disassembly without the need for prior concrete removal and the use of cost- and time-consuming auxiliary procedures.
- Further adjustments to the parameters governing the joint design are needed to optimise its performance in both persistent situations and during disassembly.

Acknowledgements

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