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Phoenix 3d-concrete-printed bridge - Falsework system and construction process development

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Abstract

Computational design and digital fabrication facilitate the construction of compression-dominant structures, such as the Striatus pedestrian bridge, built in Venice, Italy, in 2021. This paper addresses the construction process for Phoenix, a permanent 3D-concrete-printed (3DCP), unreinforced-masonry (URM) arched bridge completed in Lyon, France, in 2023. The implemented CAD workflow extends to full CAM specifications for the CLT falsework. It delivers a modular, dry-assembled solution for pre-assembled groups of blocks to be lifted into place by a construction crane. Our findings indicate increased construction process efficiency, improved control of the bespoke waffle geometry, integration of standard metal scaffolding and falsework parts, higher tolerance control, and effective global referencing. Furthermore, we incorporate adjustable gaps; thus, grouting compensates for assembly imprecisions at the supports. Crucially, falsework CLT volume utilised per square meter of bridge deck was reduced by 62% compared to Striatus, reducing single-used material and resulting construction waste.

Keywords: Circularity, Unreinforced masonry, 3D concrete printing, Discrete element modelling, Computational design, Digital fabrication, Digital construction.

1. Context

Construction, operation, and deconstruction use 48% of global energy resources, as reported in Dixit [1]. Recent research emphasizes the need to tackle high embodied emissions at construction stages, as reported by De Wolf et al. [2], especially for concrete structures, according to Nilimaa et al. [3]. In a context where circular building practices gain foreground, unreinforced masonry (URM) structures stand to deliver the ecological, economic, and functional promises of additive manufacturing technology such as 3D Concrete Printing (3DCP), reported in Bhooshan et al. [4] and Roussel [5]. This paper discusses developments in the construction process of Phoenix, a permanent arched bridge built using 3DCP and URM techniques on a digitally designed and fabricated bespoke timber falsework system.

1.1. The URM pedestrian bridges, Striatus and Phoenix

Striatus was an unreinforced masonry footbridge temporarily built in Venice in 2021 during the Architecture Biennale, presented in Bhooshan et al. [4]. Its construction verified a ground-breaking approach to concrete construction that is compression-dominant and utilises unreinforced 3DCP blocks. The bridge's design integrated state-of-the-art computational design, engineering, and robotic fabrication. Its "striated" funicular structure eliminated the need for reinforcement, solely relying on geometric design for its structural stability, as discussed in Dell'Endice et al. [6] and thus providing a sustainable solution for concrete URM structures, such as those illustrated by Georgopoulos et al. [7]. Despite its remarkable achievements, Striatus brought forth several challenges for similar projects regarding the sequencing and assembly process. These can be summarised as follows:

- 3DCP processes need further optimisation for efficient handling of the URM blocks;
- decentralised assembly, modular construction, and accurate referencing need development; and,
- building tolerances need more precise control toward higher assembly precision.

Completed in Lyon, France, in 2023 and benefitting from the experience from Striatus, Phoenix sought enhancements in all these areas, as pointed out by Dell'Endice et al. [8], an undertaking that led to a revision of its design, fabrication, and construction toward higher circularity and a lowered carbon footprint. Striatus posed construction challenges in transportation and manoeuvrability, suited for other construction systems discussed in Motamedi et al. [9] due to the substantial size of its 3DCP blocks, presented in Bhooshan et al. [4]. Therefore, strategies to overcome logistical hurdles and optimise the assembly process have become an interesting field of study in subsequent iterations. The existing assembly sequence, from support toward the centre, needed a revised approach to address tolerances during the construction process. Addressing this issue was critical for achieving a precise and structurally-sound construction. The Striatus bridge and the Armadillo Vault, illustrated by Rippmann et al. [10], Block et al. [11], and Block et al. [12], relied on unified falsework systems optimal for the former project, given the compact thin stone voussoirs, but in need of improvement for the latter.

The scope for updating the scaffolding strategy arose from the limitations of existing commercial falsework solutions in accommodating the demands of intricate and highly articulated URM structures. Unlike conventional reinforced concrete structures or lightweight prefabricated structures such as those discussed in Bodea et al. [13]and Scheder-Bieschin et al. [14], URM 3DCP structures depend on high precision, robust falsework, and precise alignment of their components to avoid structural failure, risks pointed to by Motamedi et al. [9], and Gebhard et al. [15].The geometry and tectonic assembly of the Phoenix Bridge, featuring a shallower main bridge arch and secondary bridge arch and interconnected landings linked to precast supports akin to Striatus, presented additional unique challenges. Phoenix essentially remains a masonry structure; therefore, unlike reinforced concrete bridges, Phoenix was designed for prefabrication into elements smaller than sizes common for reinforced concrete precast elements, which are usually optimised for onsite assembly, needing minimal falsework. This paper proposes a short overview of commonly used standardised falsework systems in Europe, evaluating their flexibility, structural robustness, ease of installation, and weight. We then delineate our research scope, focusing on a lightweight modular timber falsework system integrated with off-the-shelf commercial components able to interface the complex articulated URM construction. Subsequently, we detail the development of our system, highlighting its geometric attributes and assembly characteristics. Finally, we substantiate the system's effectiveness through a comparative analysis along parameters shared with the Striatus design.

2. Falsework systems for reinforced concrete cast in-situ

2.1. Standardized falsework systems

Among the standardized falsework systems commonly used in European building construction, such as Peri's Skydeck, available online at Peri [16], Doka's Staxo, described by Doka [17], and Altrad RMD Kwikform's Aluminium Beams, illustrated at Altrad [18], none possesses the features to adequately interface erect highly articulated URM structures such as the Phoenix bridge. While these systems excel in conventional orthogonal construction, they do not meet the specific requirements of our bridge design. However, our fabrication and construction team has identified an opportunity to incorporate the Doka system, recognised for its robustness and adaptability in wall and slab formwork applications. The Staxo variety, recognized for its modular framework and high structural stability, is particularly suitable for supporting heavily loaded structures. By integrating the modular system's elements into our assembly logic approach, we aim to address the unique challenges of the Phoenix Bridge's intricate, unreinforced masonry structure regarding tectonics, curvature, and load distribution. This shift underlines the need for specialized falsework systems that can accommodate complex architectural configurations, emphasizing adaptability and structural integrity beyond the features provided by conventional construction methods.

2.2. Hybrid falsework systems

The falsework system developed for constructing the Rolex Learning Center in Lausanne, discussed by Cabo and Fernández [19], featured custom-designed formwork using oriented strand boards (OSB) and height-adjustable scaffolding towers. These components were designed to support its articulated double-curvature reinforced concrete shells. While effective in delivering construction precision, the system's reliance on carbon emission-intensive materials such as OSB and intricate formwork detailing, relying on gluing and nailing, lacks convincing characteristics regarding circularity, sustainability, and reusability, adopted from the onset in all phases of Phoenix' development.

2.3. Requirements for a hybrid falsework system for URM foot-bridges

URM structures present unique design, fabrication, and construction challenges, distinguishing them from in-situ reinforced concrete shells. For this design team, the development of stone and 3DCP URM structures and their construction technology traces back to the innovations seen in the Armadillo Vault. In the indoor setting of the Venice Biennale, adjustable steel scaffolding frames and precision-cut timber formwork grillages with 3D cuts were used to align precisely with the intricately curved intrados, conforming to digital geometry, illustrated in Block et al. [11]. Here, scaffolding elements and simple hoists were preferred to heavy machinery to adhere to traditional masonry practices and avoid excessive floor loading. Similar principles were applied in constructing the Striatus Bridge, as discussed in Dell'Endice et al. [6]. Here, in an outdoor setting, a spider crane lifted the 3D-printed concrete voussoirs, one by one, starting from supports and progressing toward keystones. This approach was also used for the balustrade arches that stabilised the bridge deck against horizontal movement. The supporting falsework consisted of 21mm OSB panels designed as an orthogonal waffle structure, simplifying Armadillo's CNC manufacturing with 2D-only cuts. This adaptation allowed for efficient construction aligned with the specific needs of URM structures in outdoor settings. Still, the potential for improvement was identified in modularity, material volumes, construction sequencing, and overall circularity.

3. Design and performance of the Phoenix falsework system

The concept developed for the assembly and construction process for Phoenix aimed to ensure effective pre-assembly and clustering in building groups (BG) of the 3DCP voussoirs. Second, to have a strategy for controlling building tolerances, it was decided to start construction from the central portion of the main arch and systematically progress toward the supports. Third, CLT was selected for its mechanical properties superior to OSB, compared to the system developed for Striatus, described in Dell'Endice et al. [6], which enhances strength and durability while allowing a modular falsework structure. Additionally, we aimed for simplicity in manufacturing and assembly, as well as economy of material – eliminating machining offcuts by using 2D laser cutting instead of 3D milling - utilised for the Armadillo Vault) and discussed in Block et al. [12]. Even though Armadillo Vault and Striuatus Bridge both integrated off-the-shelf falsework components, the presented design approach introduced the functional element of the *falsework cassette* built around easy-to-preassemble 3DCP voussoirs clusters and full disassembly specifications in alignment with the project's sustainable construction focus, contributing to efficiency and environmental responsibility. Consequently, the presented falsework system can be classified as hybrid-modular, where precision interfaces with the 3DCP components are realised by incorporating a stiff but minimal bespoke CLT timber structure that ensures viable pre-assembly and structural stability during the bridge's construction process.

3.1. Reducing embodied energy

Several measures were planned to reduce the embodied energy of the falsework system:

- change the assembly approach from the masonry voussoir-by-voussoir (linear) to pre-assembled building groups (enabling parallel pre-assembly and construction)
- transition from CO2 emissions-intensive, structurally weaker OSB to more sustainable, structurally stronger CLT, and consequently
- reduce the overall material volume used through structurally stable, stiffer, modular cassettes where each CLT element fulfills a support and structural integrity function

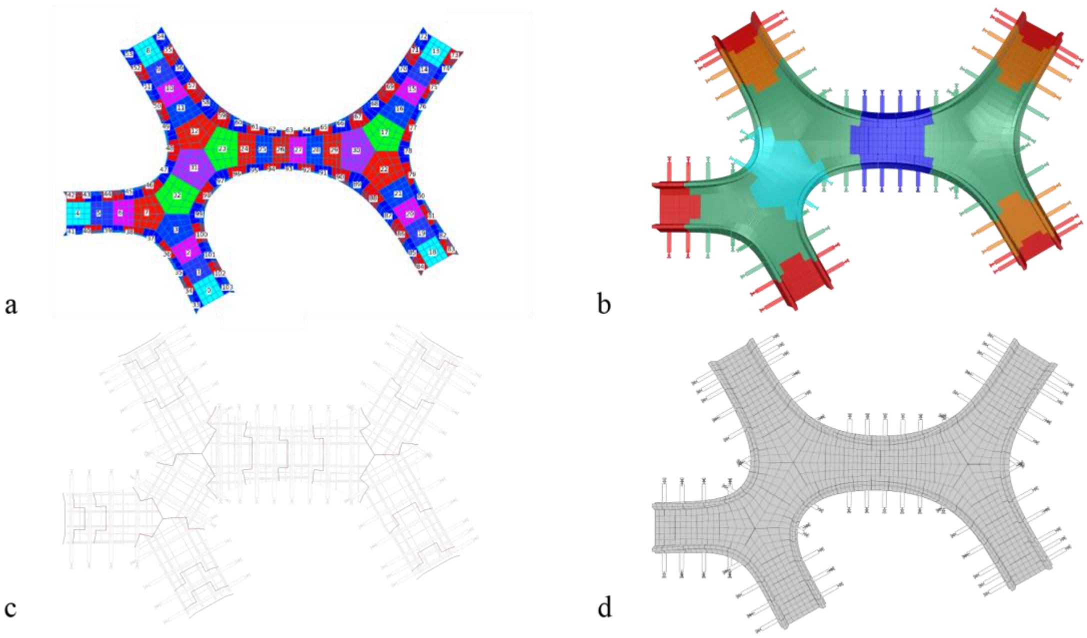

Figure 1: Falsework system development steps integrated in the overall design process. a. individual 3DCP blocks assembly model, (c) Vishu Bhooshan; b. clustering of individual 3DCP blocks in building groups, (c) Serban Bodea; c. Cassette structure generated for each building group (c) Serban Bodea; d.; Cassette structure and 3DCP components, (c) Serban Bodea

3.2. Facilitating assembly, registration, and construction

Several measures were planned to improve the effectiveness of the bridge's construction process:

- Examine assembly options that successfully mitigate geometric variability of the 3DCP concrete components in the absence of a scanning/surveying step for the 3DCP components
- Implement a dry-assembly process and propose measures to avoid stress concentration arising from any miss-alignment
- Reduce the length of the assembly process by parallelising construction steps
- Reduce cost and improve the sustainability of the construction process by prioritising the use of off-the-shelf falsework, preferably rented reusable elements whenever possible

4. Development

The previously outlined strategy for reducing embodied emissions for falsework components and facilitating assembly, registration, and construction was operationalised into a modular falsework system and parallel preassembly and construction processes.

4.1. Computational design

The proposed geometrical design process was guided by several operational steps that were simultaneously used for precision and efficiency quality assurance. The initial phase involved the automated clustering of 3D-concrete-printed (3DCP) blocks imported directly from a digital geometric model (Fig. 1a) shared between the structural/architectural design teams and the 3DCP fabricator. Through analysis of the block geometry, distinct assembly conditions were identified (Fig. 1b), leading to the clustering (Figure 1b) of components into 18 building groups:

- two main-arch building groups (BG 1-2) - Blue
- one secondary-arch building group (BG 7), - Light Blue
- seven singularity (intersection of bridge decks) building groups (BG 3, 4, 5, 6,8,9,10) - Green
- three deck building groups (BG 13, 14, 15) - Orange
- five support-interfacing building groups (BG 11, 12, 16, 17, 18) - Red

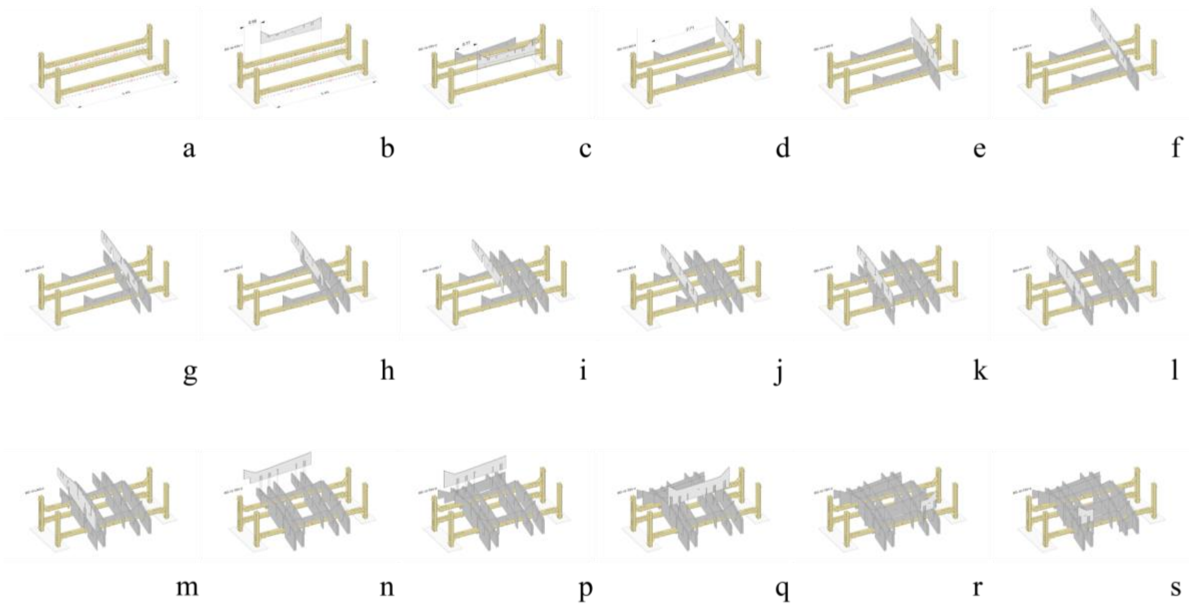

Figure 2: Cassette 10 (CAS10) constituent parts and assembly logic. a. Commercial system scaffolding wailers; b.-c. transversal falsework elements; d.-m. longitudinal falsework elements assembly; n.-s. transversal stiffening falsework elements inserted from the top; (c) Serban Bodea and Vasilis Aloutsanidis

The assembly of off-the-shelf and bespoke elements to support these building groups was termed “cassette.” A dedicated ‘cassette configurator’ was programmed using the COMPAS framework developed by Van Mele and Block [20], and in the CAD software Rhinoceros, with additional bespoke functionality in Grasshopper and Python. The extendable nature of Object Oriented Programming (OOP) implementation was kept flexible, allowing the custom selection of geometric properties, positional and registration elements, and fabrication and 3DCP component registering on a case-by-case basis for each building group. Leveraging parametric generation, bespoke geometric volumes were created based on specific characteristics such as size, area, volume, and position of each building group (Fig. 1c). The configuration process for the standardised and bespoke falsework elements was completely automated. It precisely matched the continuous bridge intrados mesh, serving as the interface with the overall bridge geometry (Fig. 1d). The resulting assembly sequence for the falsework system cassette 10 (CAS10) is illustrated in Figure 2. The construction of the cassettes was based on several geometric principles. First, the cassettes were parameterized and designed modularly and dry-assembled along a vertical insertion vector. Therefore, all cuts in the stock material were executed (laser cut) at a 90-degree angle (Fig. 2). Second, interfacing with a commercial scaffolding system was essential. This was implemented along a transversal direction - perpendicular to the bridge's arches (Fig.2a-c). Third, adequate stiffening members were placed along the bridge's arches direction to link and rigidify the transversal falsework components and interface the concrete components' geometry (Fig.2d-m). Fourth, the scaffolding components were assembled in sequence to ensure the structural stability of the system through slotting (waffle structure) without the need for any screwed, bolted, or glued connections. Fifth, registration of the concrete blocks was embedded in the timber components of the falsework and between different cassettes to ensure accurate assembly implemented at the interfaces between the cassettes.

4.2. Integrating off-the-shelf formwork and falsework systems

The falsework system comprises standard beam elements, termed "wailers," of different lengths and orientations, with standard connections (Fig. 3, blue elements). Two transversal timber elements have been developed to interface precisely with holes in these wailer elements. These interfaces that have been coordinated between the commercial system elements and the bespoke timber construction are secured with pins and wooden wedges. In contrast, the precise geometry of the waffle system's slots provides adequate precision for the system. The 3DCP elements are pre-assembled on cassettes using metallic spacers slotted and screwed on the timber elements. These metal hooks perform three separate tasks: registration of the concrete blocks on the falsework, controlling the seams between blocks, and temporarily fixing the blocks on the cassettes while preventing sliding during manipulation and assembly.

4.3. Interfaces between the URM 3DCP components

Between the URM 3DCP components, a system of individually cut flexible material components has been preassembled. These neoprene pads perform three tasks: redistribute uneven loads resulting from inevitable assembly tolerances, secure vertical metallic elements of prefabricated bridge balustrade, and provide a watertight seal to prevent infiltrations between the concrete components and water stagnation that may damage 3DCP interlayer bonding discussed by Sanjayan et al. [21].

Figure 3: Preassembled falsework cassettes, including bespoke, laser-cut CLT elements on off-the-shelf formwork system components; (c) Serban Bodea

5. Phoenix Construction

a b c

Figure 4: Preassembly process. a. Building Group 3D model, (c) Vasilis Aloutsanidis; b. Building Group assembled, (c) Serban Bodea; c. Building Group manipulation by construction crane, (c) Serban Bodea

5.1. URM Pre-assembly

The falsework assembly for each building group (Fig. 4a) was carefully choreographed in advance, adhering to the correct assembly sequence and timing to receive concrete blocks for building group pre-assembly. During the bridge assembly in June 2021, preassembly operations were efficiently carried out on two stations concurrently, streamlining the process (Fig. 4b).

Pre-assembly steps followed a pre-planned protocol, including identifying correct blocks based on manufacturer-provided numbering, placing deck and balustrade blocks with neoprene layers, as described by Dell'Endice et al. [6], installing metal balustrade fixation parts, fixing anchor elements if required, inserting metal referencing elements into machined grooves in the wooden construction, applying end neoprene layers, and thoroughly checking tolerances between all blocks. Ultimately, the pre-assembled building group, supported by its cassette, was lifted into position using a construction crane (Fig. 4c), verifying the efficacy of a digitally-planned sequence.

Figure 5: Referencing and preassembly of the building groups on pre-installed off-the-shelf adjustable scaffolding towers, (c) Serban Bodea

5.2. URM Referencing

In the preassembly of the bridge, referencing measures played a critical role in ensuring precise alignment and tolerance adherence among URM components. The system employed dual referencing methods: local referencing between concrete components and global referencing through triangulated measurements. This redundancy and robustness precisely positioned building groups in reference to at least two precast foundations with an accuracy of under 5 mm. Height adjustments of the falsework towers and the bespoke timber system's geometry were calculated to facilitate the formation of hinges between concrete components, ensuring structural integrity and alignment during assembly (Fig. 5).

5.3. URM assembly/bridge construction process

The URM construction process was developed to meet three assembly requirements:

- Integrate precast and pre-assembled structural elements (Fig.6a-b), foundations, and tension ties, respectively;
- Start of assembly from the middle of the main arch, in a sequence progressing towards the supports were accumulating tolerances we solved through grouting
- Coordinate the assembly of the cassettes at the bridge’s three singularity points to facilitate assembly along a vertical direction from the top; and,
- Decentre the bridge structure by lowering the scaffolding elements vertically and closing the pre-planned hinges.

The sequence, starting with the main arch blocks, ensured that the first cassettes were positioned securely and precisely on pre-assembled scaffolding (Fig.6c-d). This was followed by the main-arch building groups (Fig.6e-f) and main singularity points (Fig.6g-n), establishing crucial connection points within the structure. Lastly, building groups of the secondary arches were assembled (Fig.6o-q), interfacing the five precast foundation supports (Fig.6r-v), ensuring a seamless integration of structural components. This systematic approach to assembly sequence optimisation contributed to the efficiency and integrity of the overall bridge construction process (Fig. 6w).

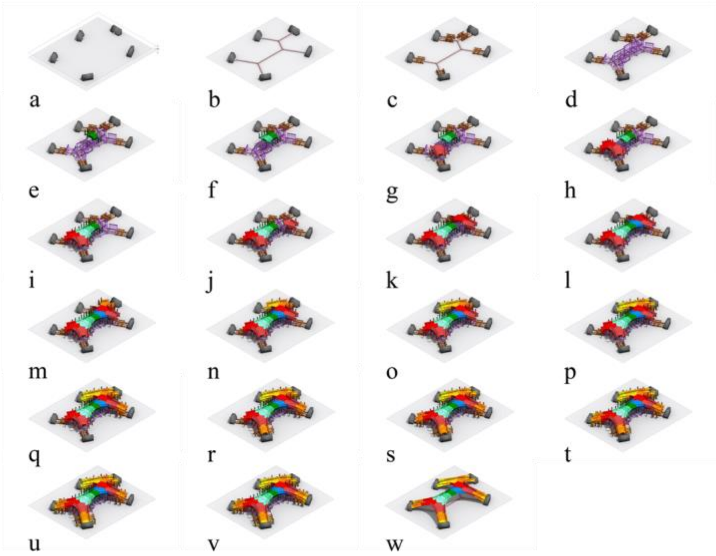

Figure 6: Phoenix assembly sequence. a. precast foundation blocks; b. preinstalled metallic tension ties; c.-d. pre-installed off-the-shelf scaffolding system elements in custom configurations; e.-v. building groups 1-18; w. falsework system removed, 3DCP components on foundations and tension ties; (c) Serban Bodea and Vasilis Aloutsanidis

5.4. Bridge decentering

The unreinforced masonry structure was decentred upon completion through the controlled lowering of the adjustable falsework towers (Fig. 7a-c). This operation facilitated the closing of pre-planned hinges between concrete components discussed in Dell"Endice et al. [6] and Block et al. [22] and illustrated in Figure 6w. This methodical approach to decentering ensures the structural integrity of the masonry elements while transitioning the assembly into its intended load-bearing state, underscoring the

Figure 7: Phoenix assembly and decentering. a. Building Groups completely assembled on falsework system; b. Decentering process, partial removal of falsework under central section of the main arch, (c) Alessandro Dell'Endice; c. Decentering process, intrados view of the main bridge-arch with falsework nearly entirely removed, (c) Alessandro Dell'Endice; d. Overview of the structure with the falsework system entirely removed, (c) Cecilia Vuillermoz

importance of digital planning and execution inherent in architectural and structural design processes.

6. Discussion and Outlook

URM bridges demand precision in structural design, fabrication, and construction, requiring interdisciplinary collaboration between planning and construction teams and substantial investment in the design phase, as also remarked by Block et al. [23]. The current formwork system streamlines assembly, integrating computational design into digital fabrication and referencing an all-encompassing design-to-construction framework. In this case, a parametric design tool harmonises geometric specifications, focusing on material efficiency. Digital design and fabrication successfully deliver a modular formwork system, embedding local and global referencing, material encoding for tolerance control, and dry fittings for recyclability. The falsework design includes CLT element discretisation, automatic dimensioning, internal features generation, referencing grooves, and automatic labeling. 2D cutting patterns optimise laser cutting on available CLT wood stock, minimising offcuts and enhancing efficiency. For an accurate evaluation of the increase in efficiency of the system compared to Striatus, as per Dell'Endice et al. [6] and Bhooshan et al. [4], a calibration of the production data between the two structures was necessary. Given the slightly different span lengths between Striatus (14m span) and Phoenix (16m span), as well as the variation in deck surface areas (43m² for Striatus, 53m² for Phoenix), our comparison is based on rescaling Striatus fabrication data similar to the analysis reported on by Dell'Endice et al. [8]. To ensure a meaningful comparison, the deck surface of the bridge was identified as the functional unit. Consequently, Striatus underwent rescaling to match Phoenix's 53m² deck surface area. This adjustment allowed for an accurate evaluation of the two structures facilitating a comprehensive comparative analysis illustrated by Dell'Endice et al. [8]. The material optimisation target of 50% reduction for the falsework system was achieved and surpassed.

Overall, a material consumption of 4.67 m^3 of timber (beech plywood, 27 mm) was calculated for the Phoenix falsework, representing a utilisation of 0.23 m^3/m^2 of bridge deck, weighing only 11,61 kg/m^2. This represents a reduction of 62% compared to the scaled estimates calculated for Striatus. Furthermore, dry assembly with minimal screwed connections (for referencing elements only) results in complete recyclability for the wooden falsework and complete reuse of the metallic elements. The absence of scanned geometric models for the 3DCP concrete blocks led to the utilisation of the ideal block geometry generated by the computational design model for the falsework system. This approach introduced errors that necessitated on-site corrections and impacted the assembly time. The off-the-shelf components also added tolerances. These tolerances exceeding 5 mm proved excessive for the URM structure, which relies on high precision to ensure the correct load transmission.

Measured tolerances required the use of telescopic falsework tubes to accommodate unforeseen tolerances. Finally, the targeted, i.e., planned for, tolerance of 20 mm between the 3DCP components and the precast foundations exceeded an average of 3 mm over the five bridge support points. Thus, the initial assembly time frame was extended from two to three weeks with extra delay due to the need to fabricate one concrete block. The impact of geometry approximation, off-the-shelf tolerances, and subsequent adjustments on the assembly timeline underscores the importance of accurate geometric data for URM. These can be mitigated by investment in surveying the 3D-printed geometry, for example, through 3D scanning of the components. In its current implementation, the system cannot cantilever over large distances, lacking the ability to span steep terrain gradients or water. These features have already been implemented in industrial bridge falsework systems such as the ones discussed by Chao and Cheng [24]. While theoretically achievable with the current approach, implementing cantilevering would necessitate stiff connections between cassettes, an underdeveloped feature. This development would require a complete revision and redesign of the decentering strategy, which is currently based on simply lowering the scaffolding towers in a vertical direction and thus closing geometrically pre-planned hinges.

7. Conclusion

This paper presented a falsework system design for URM structures, as applied to the Phoenix pedestrian bridge completed in 2023. These developments are part of a holistic approach to ameliorating the embodied carbon efficiency of discrete concrete construction. Our digital process leverages advancements in computational structural design and 3DCP. We proposed a falsework system tailored to a building application that addresses the complete building material life cycle, including construction and operation. The presented falsework system and assembly strategy demonstrate how a digital design and fabrication-driven approach adds value, saves time, and enhances circularity, increasing the competitiveness of URM structures in permanent public infrastructure applications.

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