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CONNECT4C: High-strength steel connections for circular construction

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ABSTRACT: Connect4C is a research project funded by the European Union, which aims to develop a system of high-strength steel connections for circular steel construction. It focuses on developing ready-to-use, standardized solutions for demountable, reusable, and adaptable 3D connections, taking advantage of the enhanced performance of advanced steel grades. The project considers the development of three most-used joint types: beam-to-column simple joints, beam-to-column moment-resisting joints and column splices. The combination of these three joints covers the requirements of most building structures. The paper presents the general approach of the project, the objectives pursued, and the development being carried out for the development of the system, considering specific tests and analyses.

1 BACKGROUND AND PURPOSE

An increasing tendency in the amount of carbon emissions has driven the regulatory bodies to implement new mandates. In 2020 the European Commission introduced the European Green Deal (European Council, 2020) as a comprehensive strategy aiming for a 55% reduction of carbon emissions by 2030 and complete decarbonization by 2050. As a standardized framework to support the industries to attain this target, the EU taxonomy regulation was presented in the same year (European Commission, 2020).

The construction industry is a major contributor to global CO2 emissions. According to the 2018 global status report from the United Nations Environment Programme, the sector is accountable for 39% of global CO2-e emissions (United Nations, 2018). Consequently, it is

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essential for researchers and industries within the construction domain to investigate and develop systems to guide the industry towards sustainability. In this regard, the requirements set in the European Green Deal force the construction sector towards "design for demountability and reuse" (European Council, 2020).

Steel, by its nature, offers a unique advantage for circular economy approaches due to its durability and recyclability. However, the reuse of steel structures presents a complex challenge, exacerbated by several factors, such as limited material availability, the high carbon footprint of demolition processes, and the lack of standardized design rules for reuse (Kanyilmaz, 2023). Additionally, the economic implications of these challenges are non-trivial, with the cost and industrialization level of connections between steel members significantly impacting the feasibility of reuse. Connections play a major role as they are key enablers for the reuse of steel structures. In addition, directly and indirectly, connections are responsible for 50% of the cost of a steel structure. By employing high-performance demountable connections, whereby bolted connections are preferable to welded connections (Dams, 2021), structural steel beams and columns can be easily disassembled and reused.

According to this, Connect4C aims to develop a system of high-strength steel (HSS) connections for circular steel construction. It is a research project funded by the European Union, coordinated by the University of Coimbra, involving universities and companies from Portugal, Belgium, Luxemburg, Finland, and Spain. The consortium consists of five academic institutions – University of Coimbra, University of Liège, University of Luxembourg, Tampere University, and Polytechnic University of Madrid – as well as five industrial partners – Ferpinta, Fator, Jupasa, Adão da Fonseca, and Bernabeu Ingenieros - (Connect4C 2023). The project started in September 2023, with a total duration of 42 months, until February 2027.

Connect4C focuses on developing ready-to-use, standardized solutions for demountable, reusable, and adaptable 3D connections, taking advantage of the enhanced performance of advanced steel grades (Figure 1). The project will promote a circular economy in the steel construction industry, thus leading to significant environmental savings through life-cycle thinking and digitalization, while maintaining the competitiveness of the European Economy. It strives to enhance circularity in steel construction by developing innovative, demountable, and adaptable connection systems, which are key enablers for the effective reusability of structural steel elements (beams and columns), independently of their exact dimensions (length), by allowing the possibility for large tolerances. Finally, it encourages the development of steel connections with optimized performance not only at the macro level but also at the component level, for which the use of high-strength steel (HSS) and long bolts is envisaged.

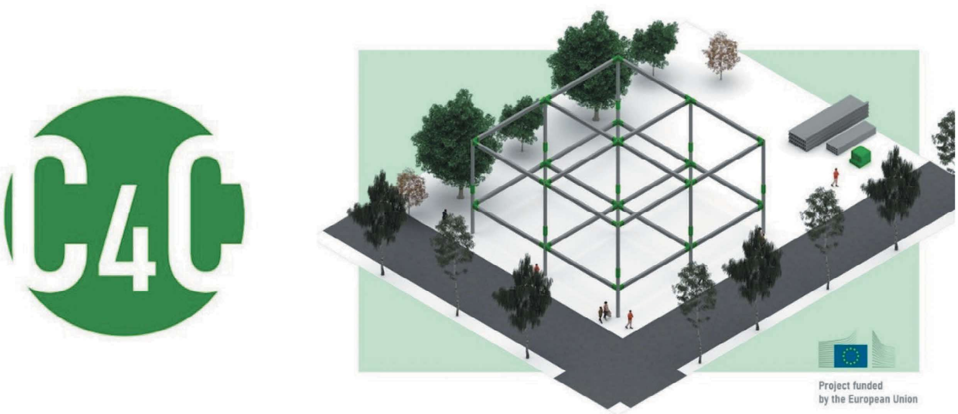

Figure 1. Connect4C. High-strength steel connections for circular steel construction.

The purpose of the paper is to present the Connect4C system at its current state of development, presenting the project motivation and objectives, the system configuration, the concept and characteristics of the demountable, reusable, and adaptable HSS connections investigated, and the next planned developments.

2 CONNECT 4C. OBJECTIVES AND OVERVIEW OF THE PROJECT

2.1 *Motivation and objectives*

The Connect4C project is motivated by two major requirements:

1. The sustainability requirements set in the European Commission Green Deal towards the elimination of greenhouse gas emissions by 2050 force the construction sector towards "design for demountability and reuse", as previously stated.
2. The demand for structural codes and design guidelines can benefit from enhanced properties of advanced steel grades.

Following these requirements, the project's main objective is the development of ready-to-use, standardized solutions for demountable, adaptable, and reusable steel structures and the underlying 3D connections using advanced steel grades and providing all the necessary tools for their practical implementation.

Namely, the following key requirements must be fulfilled by the proposed system, and therefore by its connections:

1. Adaptability, that is their capacity to adjust small geometrical mismatch between the length of members and the structural grid. This is particularly important for the optimal reuse of existing beams, whose length might not match the required span, and also for columns, allowing small variations of height between floor levels.
2. Reusability, that is, the possibility to easily reuse steel members. For this purpose, special attention must be paid during the design process to the deformation of the elements at Service Limit States (e.g., limit hole ovalization and other non-recoverable deformations, etc).
3. Demountability, that is, the capability to easily disassemble the joints and thus the full recovery of undamaged structural members. If possible, energy-expensive thermal cutting must be avoided in the disassembly process. Thus, welds on the structural members will be minimized or, if possible, eliminated and replaced by equivalent bolted solutions.

The project's main ambition is to promote a circular economy in the construction industry taking advantage of the unique potential of steel as a structural material.

2.2 *General description and overview of the project*

Connect4C system applies to non-industrial steel buildings, e.g. residential, office, and commercial low-rise and multi-storey buildings, with composite or simple slabs. The system consists of beams, columns, and innovative joints as the key enablers for the reuse of steel structures. The profiles to be used in the system for the beams and columns include open-section profiles as well as tubular profiles. The system considers three different types of connections:

1. Simple (pinned) joints. Beam to beam or beam to column.
2. Moment-resisting joints. Beam to beam or beam to column.
3. Column splices.

All the elements of the system (columns, beams, and joists) are made of carbon steel, whereby both standard and high-strength steel (HSS) will be utilized.

The system is designed for gravity loads. Lateral stability must therefore be guaranteed independently, presumably by a rigid core, or by a complementary bracing system, which ensures the behaviour of the system against horizontal wind and seismic actions. Hence, no wind nor seismic loads are considered in the analysis and performance of the system. Besides, the system does not consider the design and analysis of the foundations, nor secondary elements such as stairs, façades or claddings.

A variety of beam spans, beam spacing, and loads is considered, carrying out a parametric study. Beam spans range from 4.05 m to 16.20 m, considering a modular length of 1.35 (from 3×1.35 m to 12×1.35 m); Beam spacing ranges from 2 to 3 m, standard spans covered by steel decks; and total loads, including permanent and live loads, are considered as light (q_k □

5.5-6.0 kN/m^2), medium ($q_k \cong$ 7.0-8.0 kN/m^2) or high loads ($q_k \cong$ 10.0-11.0 kN/m^2). Besides, the system and the designed connections will allow a tolerance of up to 250 mm.

To guide the development of the system and to verify its applicability and efficiency, a representative building is considered. The reference building is first designed considering standard connection solutions and subsequently redesigned to incorporate the structural characteristics of the Connect4C connection system, including the implications of demountability and large tolerances. Figure 2 presents the considered reference building. It is a 7-floor high office building, with floor plan dimensions of 28.35 (21×1.35 m) × 16.20 (12×1.35 m). Beam span ranges from 5.40 m (transverse beams) to 6.75 m and 10.80 m (longitudinal beams), while the considered floor height is 4.0 m. The building is braced by an inner core, so horizontal loads are not considered as previously mentioned. The building is considered both with simply supported and moment-resisting connections.

Besides, several experimental campaigns have been developed or are under development, for the characterization of innovative and HSS components considered in the different connection configurations. These include the analysis and experimental campaign of new components, such as L-stubs, the extension of existing components to HSS, and the long bolts. The purpose is to characterize the different components, to consider and incorporate their actual behaviour in the different types of considered connections.

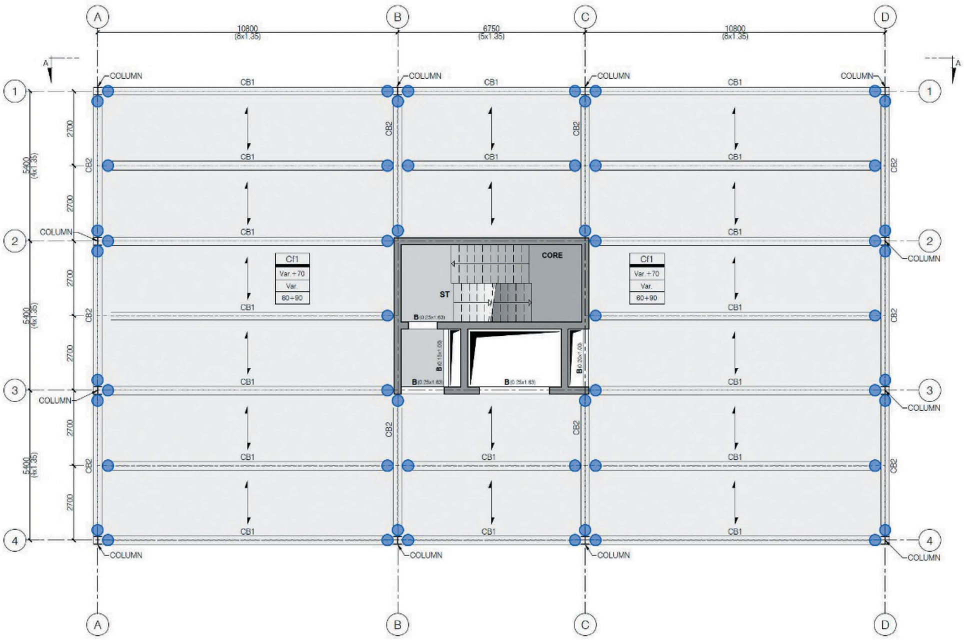

Figure 2. Reference building configuration.

3 DEMOUNTABLE, REUSABLE AND ADAPTABLE HSS CONNECTIONS

3.1 *Simple joints*

The simple joints will make use of an adjustable L-shaped connection element with slotted holes. This component will be responsible for the connection between beams and columns, offering horizontal adaptability to the joint structure. The studied simple joints include connections between open-section beams to tubular columns and closed-section truss girders to open-section columns, as well as open-section beams to open-section columns. To accommodate column profile adjustments in both old and new buildings, large tolerances of 230 mm between beam ends and column centrelines will be allowed. This will be achieved using L-shaped fin plates with long slotted holes. In the tests, the following parameters are varied: beam type, column type and size, high-strength steels, and eccentricities. The following aspects will be investigated: bending resistance and rotational capacity of the joint considering preloading of bolts, failure modes, and reusability.

The connection between open-section beams and tubular columns is a challenge in the context of joint design. The proposed connection system will use the L fin plate as the main element. However, it will also make use of an additional component, responsible for enabling the connection of the L fin plate with the circular column.

The proposed connection system also considers the possibility of a connection between open-section columns and the truss girder. To do this, it is necessary to investigate the use of the joint in the case of tubular profiles being used as truss sections. In the test, different eccentricities will be considered depending on the positioning of the column in relation to the connection with the truss. Thus, in the first test, the truss will be connected to the column flange and in the second test to the column web. This will allow for a better understanding of the behaviour of the connection in the case of column-truss connections.

The proposed joint can also be used for connecting more standard member configurations, such as an open section beam to an open section column. In this case, the experimental test will be carried out to assess the stiffness variation in the connection with the use of an extended plate in the beam-column connection. This will also promote the use of more bolts in the region of the column-L fin plate connection.

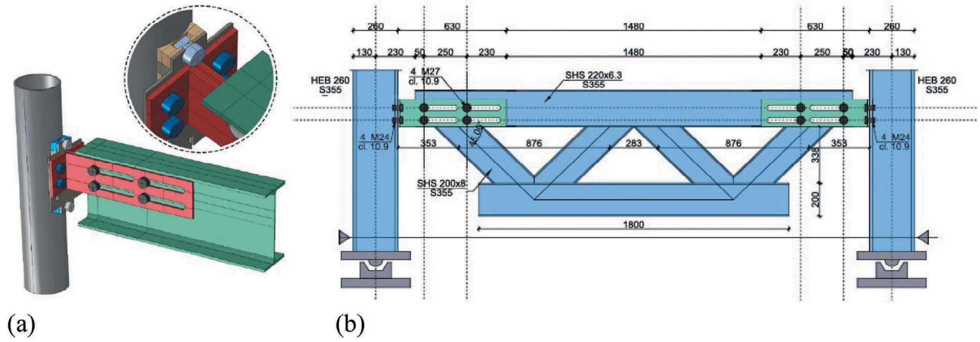

Figure 3. Simple joints. a) Open section to tubular columns. b) Truss girder to open section columns.

3.2 *Moment-resistant joints*

Moment-resistant joints are considered for both beam-to-beam and beam-to-column connections, according to the considered configuration (Jankovića, 2023). First of all, a study was conducted to evaluate the influence of the continuity of a beam on its supports, concluding that the span increase provided by the continuity of the beam on its supports is larger if plastic analysis is performed. According to this, a strategy of developing semi-rigid connections is considered, in which the resistance of the connection is below the resistance of the beam, providing reasonable continuity with small rotation for SLS, and moderate continuity with large rotation for ULS.

An innovative demountable double-sided beam-to-beam moment-resisting connection for open sections has been developed and validated. This joint ensures continuity between the two connected members by transferring the internal forces at their interface while allowing for a possible change of cross-section dimensions. The studied connection is assembled from independent parts, put together with conventional and long bolts, with no additional welding, and therefore completely demountable. Figure 4 shows the proposed connection. One element, a “hyperpack”, is added to the connection (in light and dark blue in the image), in comparison with conventional steel joints, to be able to adapt and adjust to different structural systems. Its purpose is to allow different joist lengths to be connected equally effectively to the main beam. As can be seen in the figure, the connection includes four hyperpacks, disposed at each end on both sides of the beam.

The hyperpack is formed by five steel plates (S355 or HSS S690) welded together and is used to link the main beam with the joists. A large number of bolt holes are provided on the hyperpack, with a distance of 50mm, which enables joists to slightly move in the longitudinal direction and adapt to various spans. The hyperpack is not a closed box to allow free access to all parts of the connection. The full connection between the joist and hyperpack is provided with the assistance of several conventional 10.9 bolts, while 4 conventional bolts on the main beam web mostly transfer shear force, the long bolts are responsible for transmitting the tension force. To avoid the bending of the long bolts and any undesired effects, slotted holes are provided on the main beam´s web. FEM analyses have been performed to check the behaviour of the connection and to confirm whether the different elements stay in the elastic zone throughout the life span of the structure, or if there is no significant plastification of the parts, so the connection can be reused. According to this analysis, small adjustments are currently undertaken, considering additional bolts stiffeners and plates, but the performance of the proposed configuration is confirmed to be adequate.

Besides, a similar configuration is currently being studied for the case of beam-to-column moment-resisting connections, considering tubular column and I profile beams (Figure 5). As in the case of the beam-to-beam the moment continuity is achieved by means of the long bolts, and according to the undertaken preliminary analysis it is possible to transfer up to 60-70% of the beam resistance, which means the connection is semi-rigid with sufficient rotation capacity. The shear efforts are transferred from the beam to the intermediate element by the conventional elements and then from this element to the column by means of a set of welded steel plates implemented on the column every certain distance in height, allowing for vertical adaptability of floor levels. It is important to note that the connection assures moment continuity of the beam, but is simply supported by the column so there is no transfer of bending efforts from the beams to the columns.

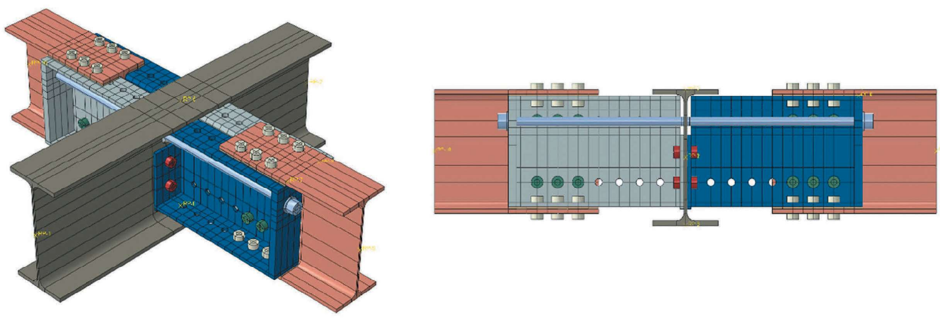

Figure 4. Moment-resistant joint. Beam-to-beam connection.

3.3 *Column splices*

Column splices are expected to provide vertical adaptability, as well as ductile failure mode which does not impair the reusability of the columns due to excessive local plastic deformation. Several solutions have been considered and studied, to assess their feasibility, reusability, adaptability and efficiency, according to the C4C system. The different column splice solutions can be sorted into two main categories, depending on how the load is transferred: bearing splice, and cap and plate.

First, in the bearing splice typologies, the load is transferred from one member to another through shear lap joints activating the bearing at the bolt holes and shearing of the bolts (Figure 6a). This kind of joint is commonly used in practice and the formulae for designing such connections have been recently reviewed in the prEN1993-1-8. However, from the undertaken study, it appears that this kind of connection is quite inefficient even in the most favourable case of pure axial load. Indeed, the use of long 10.9 bolts allows for achieving a bearing capacity that is smaller than the column bearing capacity. Moreover, the failure modes in this type of configuration are either brittle or lead to significant yielding in the column faces and so to significant local deformations that impair the reusability and go against the project goals and philosophy of the system. This type of solution is therefore disregarded.

The other main types of splices commonly used in practice are based on end plates. In such a connection, when the axial load is predominant, the latter is mainly transferred by contact with the plates and the bolts are mostly there for constructive purposes and to transmit potential moments and/or shear efforts. This kind of splice is quite efficient but cannot be used as such in the Connect4C system since it provides no adaptability and the failure of any element would immediately impair the reusability of the columns. To tackle these issues, an intermediate piece

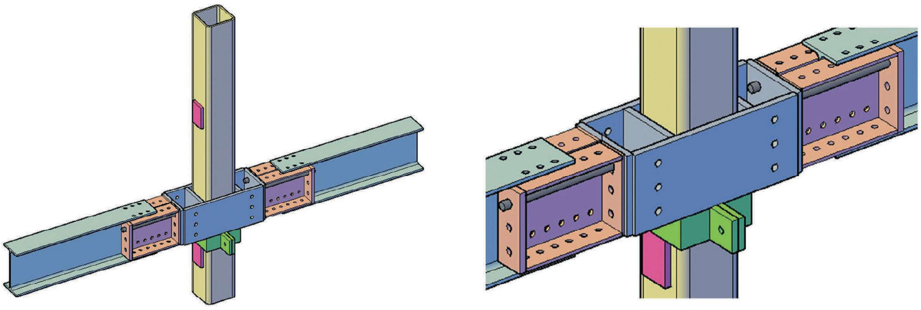

Figure 5. Moment-resistant joint. Beam-to-column connection.

acting as a fuse element can be placed between the columns. This joint configuration is similar to "classical" endplate column splices but uses an intermediate piece with end plates at its extremities, the latter being calibrated to act as a fuse element in case of overload, as shown in Figure 6b while allowing for vertical adaptability.

Several solutions and configurations have been then considered for the intermediate piece, including cleat pieces, UPE type pieces, T-stub pieces, cross-pieces solutions, cleats and end-plates or plug-in pieces. From all these, the intermediate cross-piece solution has proven to be the most appropriate in this case, meeting the different system requirements. With this type of piece, as shown in Figure 6c, the shear is carried by the webs while both the bending moment and the axial loads are transmitted through the flanges. This solution is also very convenient since it no longer requires column splice end plates extending outside the column dimensions and thus there is no more imposition on the splice location. Moreover, the slotted holes in the end-plates of the intermediate piece allow to cover a large range of profiles with one unique piece and variation of geometry as well. In addition, this unique piece can be used to connect both H profiles and tubes, circular or not, the only requirement to connect tubes being to have hand holes near the column end to allow for bolt tightening. Finally, this intermediate piece can also be used to connect beams if placed at the level of a floor.

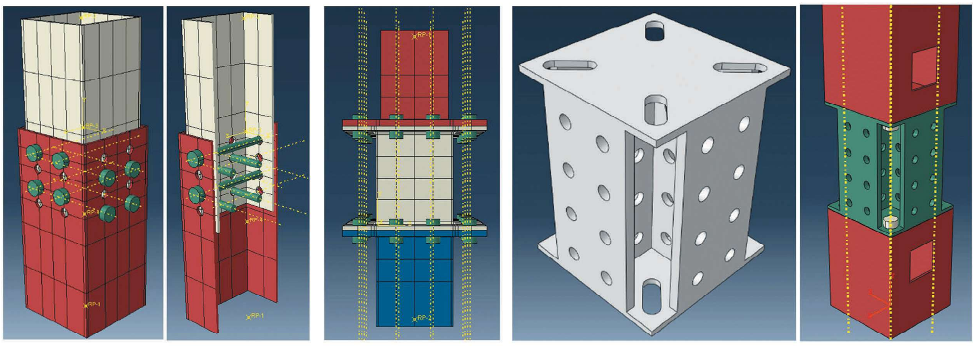

Figure 6. Column-splices. a) Bearing splice typology. Disregarded. b) Cap and plate typology. c) Intermediate cross-piece solution.

4 CONCLUSIONS

The paper presents the current development state of the Connect4C research project, an innovative system of high-strength steel (HSS) connections for circular steel construction, funded by the European Union. In particular, the project considers the development of three most-used joint types: beam-to-column simple joints, beam-to-column moment-resisting joints and column splices.

The presented connections assure a great horizontal adaptability, obtained by innovative configurations, so the beams can slightly move allowing tolerances up to 250 mm, as well as vertical adaptability of the connection enabled by the occasional supporting welded plates, and column-splices for the column's adaptability. The connections are completely demountable since all the connections are bolted. Innovative elements are included in the study, such as L-stubs, long bolts, hyperpacks or intermediate cross-piece splices. Also, the potential benefits from the use of the HSS are considered. Finally, the reusability of the connections is considered by ensuring that there is no plastification in the parts that can lead to any damage.

Next and further developments of the project consider the following key points:

1. To complete the analysis and refine the configuration and design of the different connections, taking also into account the results of the experimental campaigns.
2. To coordinate and assure compatibility between the different types of connections, according to the characteristics and requirements of the system.
3. To study and coordinate the compatibility of the Connect4C connections with the reuse of existing profiles, so that these existing profiles require as little adaptation process to the Connect4C system as possible.
4. To complete the parametric study, covering the established range of loads, beam spans and beam spacing.
5. To evaluate the ConnectT4C system, using the reference building study, that will be redesigned incorporating the structural characteristics of the C4C connections, with a lifecycle perspective, covering the environmental, economic and social dimensions.

Besides, the work and developments to date allow us to advance some of the system limitations, which are challenges and opportunities for future developments. These include the extension of the Connect4C system to consider horizontal wind and seismic loads, by the integration of braced and/or rigid frames and the connections required in these cases, and the system integration and compatibility with demountable and reusable foundation systems.

The purpose is to contribute towards digitalization and circularity in steel construction, resulting in high levels of sustainability and adaptability over the lifetime of a building.

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