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Application of Water Jet Cutting and Optimization Problems in the Development of a New Concrete Construction System

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Abstract

The progression of new automated manufacturing techniques and the rise in human resource costs necessitate diversification in traditional construction methods. In the development of novel techniques, modern equipment should be incorporated, and optimization techniques should be applied. This study explores the potentials of a automated water-jet cutting machines for production innovative optimized construction, which can be assembled utilizing the dry connections. Using a Water Jet Cutting Technique (WJCT) for cutting elements enables the construction of free-form elements. Consequently, after proposing and detailing some dry connections that can be produced by a WJCT, this study delves into applying a meta-heuristic algorithm to determine the optimum layout of curved beams. Following a description of the general form of the structures, the water-jet production process, and assembling scenarios for a two-floor building are presented. The expeditious performance of the optimization algorithm, coupled with the manufacturing and assembly of a scaled-down physical model, highlights the practical applications of the proposed optimized system.

Keywords: Concrete, Water-Jet, Building, Dry connections, Optimization, Precast

1. Introduction

Precast building structures significantly advance modern construction techniques, offering efficiency, durability, and sustainability advantages. This method involves producing standardized building elements in a controlled factory environment before assembly on-site [**1**]. The precision achieved in the factory ensures high-quality components, minimizing variations and enhancing structural integrity. Precast construction reduces on-site labour and accelerates project timelines, resulting in cost savings and a diminished environmental impact compared to traditional methods [**2**]. The versatility of precast elements allows for innovative design solutions while maintaining structural efficiency, making them a compelling choice for contemporary projects. They blend engineering excellence with sustainable practices, making the application of new optimum building systems highly desirable.

WJCT has emerged as a pivotal method for precisely cutting concrete in various industries. Using a high-pressure jet of water mixed with an abrasive material offers advantages like reduced environmental impact, minimal dust generation, and improved safety for operators [**3**], [**4**]. Water-jet cutting preserves concrete's structural integrity without inducing thermal stress or micro-cracking, enhancing durability [**5**]. With the ability to accommodate CNC technology, water-jet systems execute complex cutting patterns with unparalleled precision, transforming concrete cutting applications [**6**].

Concrete dry connections represent a significant advancement in structural engineering, offering a versatile and efficient alternative to traditional wet connections. These connections rely on mechanical fasteners or interlocking elements instead of wet materials like mortar or grout, impacting various structures such as bridges, buildings, and infrastructure projects [**7**]. Dry connections provide several advantages, including reduced construction time, increased design flexibility, and improved construct-ability. They enhance precision in assembly processes and demonstrate superior performance in seismic events, eliminating potential issues associated with wet connections like differential settlement and enhancing overall structural resilience. Concrete dry connections signify a substantial leap forward in modern construction practices, offering a sustainable and reliable solution for various structural applications. Experimental and numerical analyses have evaluated a wide range of connection geometries, showing that elements connected by dry connections exhibit high capacities compared to exact monolithic elements [**7**]. Consequently, developing a concrete building system considering the capabilities of the water-jet technique and dry joint geometry can be beneficial.

In structural engineering, the emergence of Machine Learning (ML) has sparked a new wave of innovation and efficiency. With increasing computational power, engineers can employ complex algorithms to tackle intricate problems, leading to a paradigm shift in structural design capabilities. ML encompasses various techniques, including Neural Networks, Fuzzy logic, data mining, and optimization algorithms, utilized by researchers to interpret performances of dry joints and convert discrete data into continuous formats using Fuzzy logic [**9**]. Optimization in structural design is a cornerstone of modern engineering, employing advanced computational techniques to achieve efficient solutions. Engineers strive to balance conflicting objectives through mathematical algorithms and computational models such as minimizing material usage, maximizing load-bearing capacity, and ensuring structural safety. Notable studies, like Sigmund's work on topology optimization [**10**], highlight the trans-formative potential of mathematical optimization in creating innovative designs. Engineers can achieve unprecedented outcomes by iteratively refining structural configurations based on predefined criteria.

Integration of ML techniques enhances optimization, enabling engineers to navigate vast design spaces swiftly and precisely [**11**]. This synergy between traditional optimization methods and cutting-edge computational approaches marks a new era in structural engineering, unlocking the full potential of data-driven insights and computational power. Meta-heuristic algorithms have demonstrated proficiency in addressing a wide range of problems in concrete structure design. These algorithms have successfully tackled various aspects and types of problems. For example, in designing the optimal beam layout for a building floor, an optimization algorithm interfaced with finite element (FE) software was employed [**12**]. Similarly, optimization approaches for allocating desirable locations to connections in precast concrete buildings were developed [**13**]. Furthermore, a meta-heuristic algorithm was studied to find optimal locations for walls and columns in a building [**14**]. The optimization of wall and column placement, considering forces, demands, and construction considerations, often leads to irregular column locations, necessitating unique beam layouts and optimization approaches, as discussed in this article.

2. Discussion

This study aims to explore three key techniques for designing and proposing a new building system:

1-Water-jet cutting: The optimization approach for finding the optimal layout of a beam will be described. 2-Dry connections: Various types of concrete dry connections, manufacture-able by Water-Jet cutting, will be briefly presented. 3-Optimization algorithms: An example will illustrate the optimization process for designing a two-floor building.

2.1. Optimum beam path planning

Due to the application of WJCT, the production of beam, column, and floor elements doesn't require individual form-work. This reduces costs and difficulties, including the storage of form-work and the impact of ageing on their precision, and allows engineers to easily design optimum elements, contrary to the normal construction technique.

Optimizing the structure involves considering a wide range of components in different steps. One crucial step, which follows the optimal location-allocation of columns [**13**] and finalization of the architectural design, is finding the optimal layout of the beams. This is done while considering different architectural elements as obstacles.

This section will discuss the adaptation and application of known optimization techniques through an example. Figure.(1) illustrates the selected example, which represents one part of the entire building model considering the locations of columns and assumed obstacles, including an elevator, a round staircase, and a light rectangular void on the right. In this case, the optimisation algorithm is particle swarm optimization (PSO), which is selected and interfaced with the defined beam layout problem (BLP). MATLAB was chosen as the coding platform, and the BLP was defined as:

1. Definition of the lines

   Unlike normal operations, the optimisation results are not single digits but a line. Similar to time series, these results encompass a range of data for each beam, addressable by different continuous definitions or place-dependent foundations (similar to robotic moving lines). Essentially, the solution transforms a line with infinite parameters into limited optimized digits. Various approaches can be chosen, such as: 1-Dividing into smaller lines (piece-wise linear), 2-defining a function with specific components (e.g. Parabolic function or complex series), 3-Combining foundation assignment and piece-wise lines (e.g. spline), 4-Utilizing artificial neural networks or Fuzzy logic. The spline function (spline(x, y, n) in this study) was selected for simplicity and available MATLAB codes. The number of nodes (n) during the design of the optimum beam, considering the complexity of the problem and obstacles, can be chosen. Here, the coordinates of two columns (start: (0,0), end: (7.96m, 4.5m)) are selected as the boundary conditions, Fig(1).

2. Creation of a random solution and border-beam consideration

   In typical optimization algorithms, initial runs involve using random data to calculate initial results and costs. Subsequently, algorithms determine directions for improvement by comparing costs from these initial runs. After multiple experiments, the most optimum solution is selected. The initial random data consists of coordinates generated by different randomization functions in MATLAB, representing points on the spline. The number of these points depends on the layout's complexity and the desired number of curvatures (n), a parameter determined by the operator . Constraints must be incorporated into the algorithm, especially considering the limited area, such as the space between four surrounding beams. Introducing penalties for violations is a common strategy for handling obstacles while optimizing costs. Additionally, random solutions for initialization require definition, and the range of random initial data can be confined to coordinates within the beams' surroundings (e.g. using $unifrnd$).

3. Creation of the Spline

   To define the spline in each iteration, a range of x and y coordinates is required to represent the beam's trajectory. The initial and final coordinates correspond to the coordinates of the columns. The points in between, representing the optimum points, are calculated, beginning with random

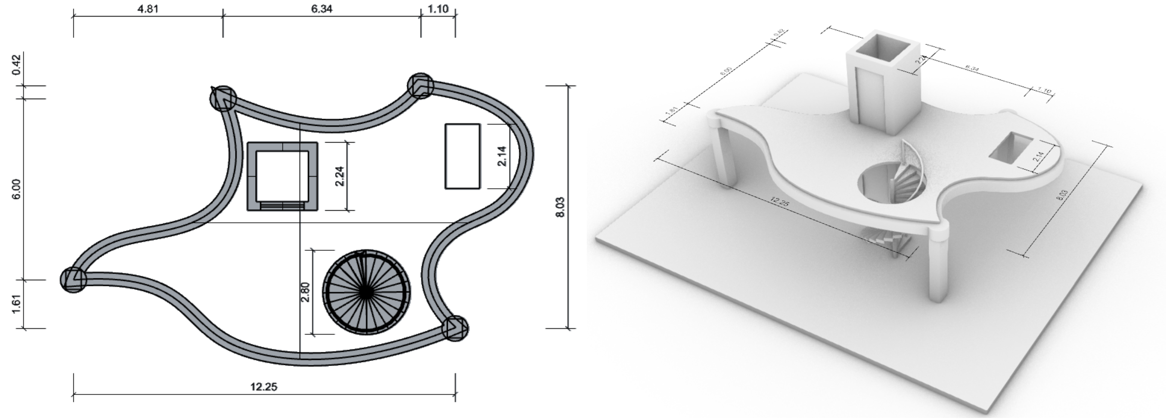

Figure 1: Definition and application of beam layout optimization based on architectural plan and column locations, Floor Plan (left), and perspective (right)

numbers. Typically, this is defined based on 100 independent points, corresponding to the steps made by $linspace$ to define x and y coordinates. This approach is based on an independent factor, ensuring a consistent representation of the beam's path.

4. Location of the Obstacles

   The locations (x, y) and dimensions of obstacles, such as the elevator, staircase, and void, were gathered from the architectural plan. This adjustment tailors the optimization area to the building floor (see Fig.(1)). To define an obstacle, the distance (L) between the centre of the obstacle (e.g. staircase) and each node on the spline, which can be easily calculated in each iteration, should exceed the dimensions of the obstacle (e.g. the radius of the staircase, r = 1). As the number of obstacles increases, the calculation should be performed for each one, either as a multi-optimization or by the simple summation of violations ($v = \text{mean}\max(1 - \frac{L}{r}, 0)$), considering it as a minimization optimization.

5. Beam Length

   Various components in calculations should be considered; however, given that the primary objective of the layout problem is to find the shortest possible trajectory between two points, the length of the beam should be calculated as a cost. As the spline is constructed based on the specified points, the summation of the absolute distances between these points can be calculated, for instance, using the command $sum(\sqrt{\text{diff}(x^2, y^2)})$. This value can then be compared to the distance between the columns to evaluate its magnitude.

6. Bending, shear and torsion optimization

   In structural analysis, various forces, such as shear, bending, and torsion, are crucial for beams. These forces, coupled with applied loads, are contingent upon the geometries of the structural elements. This study introduced an additional penalty for violation, accounting for torsion, shear, and bending in the primary direction in a simplified manner. Bending and shear calculations employed a straightforward approach for a beam supported by two hinges. The weight of the beam, presumed to be a fixed section, was factored in as a function of length. Similar calculations were conducted for a straight beam connecting two columns, with subsequent comparison of the results.

   Because of the obstacle, the algorithm cannot directly connect the two points, requiring curvatures in the beam's trajectory. These curves introduce torsion in the beams, typically insignificant in conventional buildings. Several methods are available to calculate forces in the beams, including static simplifications, defining stiffness matrices, or interfacing with finite element (FE) software.

For simplicity and computational efficiency, the cost was calculated by summing the distances between midpoints of piece lines in the curved beam and corresponding points on a straight beam between columns Fig.(2.1.)). Each bending, shear, and torsion factor was normalized by dividing by their maximum values to render them unit-less and comparable. Thus, the linear summation of these factors indicates the force and geometric violations which require optimization.

7. Penalty coefficients

   The cost can be formulated as a multi-objective optimization or a weighted sum, where the summation of normalized penalties is used, as in the current study. However, assigning individual factors to each violation can adjust the penalty amounts based on their influence on the optimization process.

   This study's primary objective is to demonstrate the feasibility of solving a simple problem. Therefore, the penalty factor for avoiding obstacles, which is essential, has a higher coefficient compared to other factors.

8. Particle Swarm Optimization Algorithm

   The PSO algorithm was chosen as an efficient optimization method for optimizing the layout, although other optimization algorithms could also be interfaced. Notably, the typical PSO is defined in 1D, whereas for layout optimization, two-speed directions are required. The algorithm reached optimum layouts in fewer than 200 iterations, with a population size of 200. The Personal and Global Learning Coefficients were set to 2, and the weight inertia and damping factor were set at 0.99 during this operation.

This operation was managed on one side of the building between the pre-selected beams, while it can be a progressive optimization operated one by one utilizing a loop regarding every two columns as the beginning and target point of the spline. In this regard, the mentioned penalty and randomization part must be changed to reflect the probable intersection of the beams.

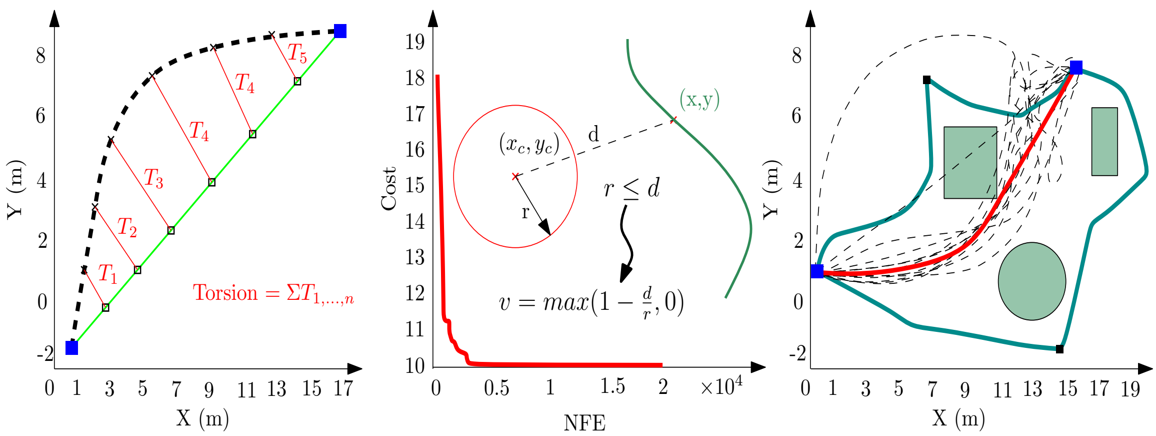

Figure 2: Optimizing beam layout using Particle Swarm Optimization (PSO), considering obstacles such as voids, elevators, and staircases.

2.2. Dry Connections for Water-Jet Cutting Technique

Designing concrete dry connections encompasses various challenges for designers, including: 1. Ensuring proper force transition (e.g. bending or shear) from one side of the elements to the other, with the joint's capacity comparable to that of the element. 2. Designing and allocating embedded re-bars to function primarily under tension. 3. Considering forces in multiple degrees of freedom. 4. Achieving a high degree of interlocking to prevent chain collapses, especially during construction. 5. Respecting assembly scenarios and ensuring the feasibility of manufacturing the elements.

The conventional method for manufacturing precast and cast-in-place elements involves using formwork, but it's costly and impractical for producing intricate dry geometries. Robotic CNC offers versatility but faces limitations in accessibility, movement, and potential obstacles from the clamping system. While it can produce a diverse range of geometries, its high cost, prolonged manufacturing time, and potential impacts on precision due to tool erosion pose challenges in its utilization [**7**], [**6**]. As utilized in this study, the WJCT presents an alternative approach with higher precision than traditional methods, particularly during the assembly process.

5-axis-robotic water-jet machines can rotate the nozzle, allowing for perpendicular and 3D cuts at various angles. However, it's crucial to note that these 3D movements don't result in 3D geometries. Despite their versatility, the cuts must extend to the water pool to relieve pressure, depending on the machine making precise cuts deeper than, e.g. 10cm might be unfeasible. Figure (2.2.) illustrates ten designed connections achievable with a WJCT. This limitation necessitates simpler geometries, which may be more desirable for structural elements considering other construction factors.

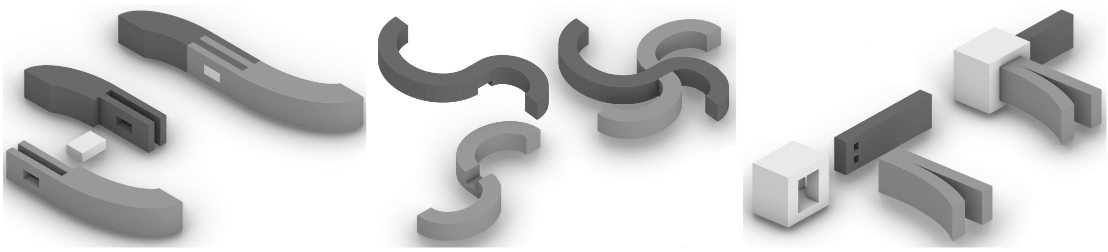

Figure 3: Proposed geometries of Dry Connections for Water-Jet Cut

Three types of beam-to-beam connections were proposed, produced, and physically tested using other techniques, such as CNC and printed formwork in previous studies [**15**]. These connections, produced by water-jet, exhibit higher resistance than monolithic elements. Combinations of these connections also allow for the construction of flooring systems (see Fig.(2.2.). The cutting lines for the production of these elements are also illustrated. Notably, some elements can be produced with a single-direction cut (e.g. Fig.(2.2.). Generally, for manufacturing most geometries, two cuts or three cuts (Fig.(2.2.)) might be needed. These cuts, applied from different directions, require two or three consecutive rotations of

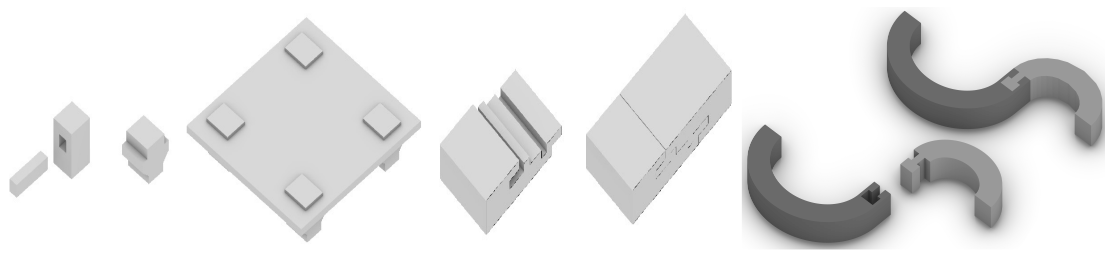

Figure 4: Proposed geometries of Dry Connections for Water-Jet Cut

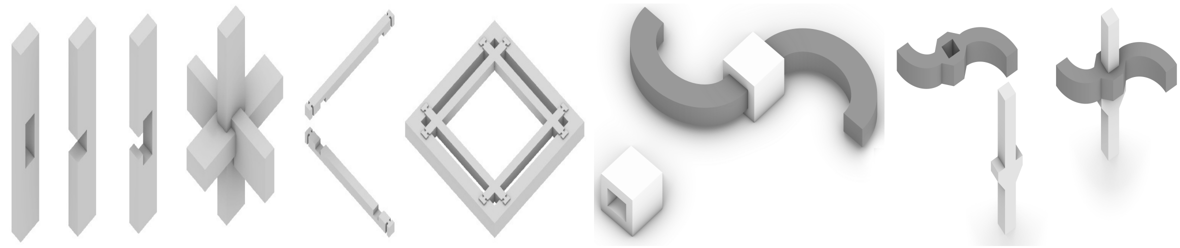

Figure 5: Proposed geometries of Dry Connections for Water-Jet Cut

the elements to be applied from each side. While these limited geometries suggest the possibility of creating complex structures. Additionally, dry connections are not the sole type of joints that can be applied; for example, a water-jet can be utilized for drilling holes or cuts to later accommodate steel screws or plates. Fig.(2.2.) displays the two types of connections used in the design and manufacturing of the building in the following section.

2.3. Manufacturing and Assemblage:

The approach for designing the optimal layout of each beam was discussed, and potential connection geometries were presented. As this study introduces an innovative concept for a new building approach, it is essential to provide an overview of the entire process. However, careful consideration of details is necessary, encompassing the design of complete beam layouts, potential intersections, and the intricacies of re-bars and their production techniques, which will be explored in future studies. Presenting the general idea of the system requires a description of the production method and the assembly process.

To illustrate the production method and subsequent assembling scenario, a two-floor building was utilized as an example (see Fig.(2.3.)). In this chosen geometry, the aim was to showcase the capability of the presented approach in creating free-form geometries, enhancing optimization, and allowing for more desirable arches. Moreover, the building incorporates various beam and column joints, with columns between 2-4 beams and features open facades (unspoiled opening).

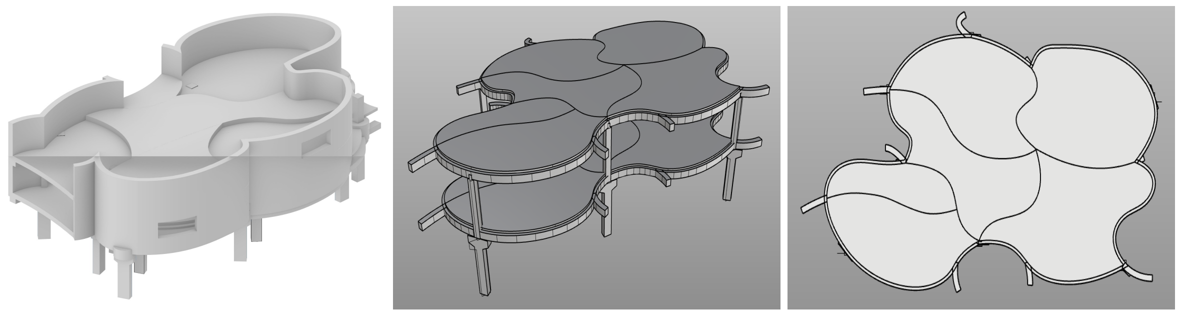

Figure 6: Selected geometry of the building structures

The design process of the building after having the general plan starts with - a general standard architectural and then structural design, - and the optimization process in which optimum places of the columns or walls were operated, leading to the irregular optimum location of the 11 columns [**14**]. In the next step, the optimum shapes of the beams were designed using the discussed beam layout optimization. - then, two types of displayed connections were used regarding the limited desirable dimensions elements and beams - Finally, the beams utilizing connections were segmented Fig.2.3., and one more time, the geometries were structurally designed to achieve the dimensions.

The elements can be manufactured after the design and geometries (floor, beam and columns) are com-

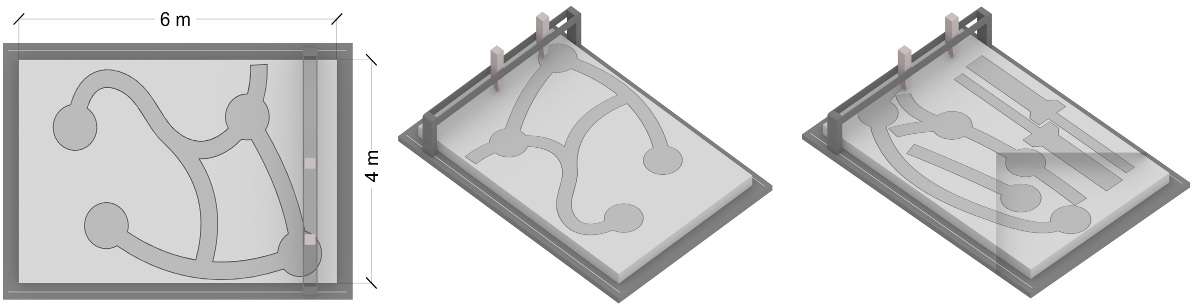

Figure 7: Nestling multi structural elements in the water-jet cutting unit

pleted. Since the main aim is to avoid the usages and difficulties of formwork for producing unique elements, the elements should be produced in two steps. The first step is roughly making the concrete elements, and the second step is using the WJCT for precise cuts and forming the joints. Manufacturing the concrete elements can be managed using robotic shotcrete or extrusion, which can print curved linear elements. The elements with rough geometries can then be cut precisely.

An alternative approach involves creating planar ($\simeq 2D$) concrete elements, such as those with the thickness of the beams. These planar elements can then be subjected to water-jet cutting to produce multiple individual elements, such as beams. Figure (2.3.) illustrates a water-jet unit and planar elements for cutting out the beams. Industrial water-jet machines come in various dimensions, with the capacity to produce elements changing based on factors like maximum water pressure and cutting space size. For instance, a machine capable of cutting a 30cm thickness with a $4 \times 6m$ cutting area is feasible.

Considering a building floor area of approximately $75m^2$ and the selection of five beams during the design, the longest beam's length is $7.2m$, and the height of all 11 columns is $6m$. With the assumed machine specifications, all elements can be produced. However, adjusting the number of columns to reduce lengths and thickness or selecting different beam geometries with shorter lengths is possible.

To efficiently cut out beams from planar elements and minimize the production of excess material, it is crucial to position the beams and columns as close to each other as possible. Figure (2.3.) demonstrates how the linear elements are arranged. In this specific example, high amount of the total concrete was lost due to the arrangement made by the operator. This loss could be significantly reduced by employing individual element printing or using optimization solutions like the Knapsack problem (Nestling). Additionally, incorporating more head-to-head beam connections can notably reduce material waste and associated difficulties, as depicted in Fig.(2.3.).

The building primarily comprises two groups of beams, facilitating a more straightforward manufacturing and assembling process. In the zones where beams connect to columns, the column's dimensions change at each floor level to accommodate the beams positioned above the corbel. During the assembling process, the beams are sent down from the top level of the building to the corbel support while the column is in the designated connecting hole in the middle of the beam. This process can be repeated at each floor level. Pin joints can also be employed to simplify the process. Furthermore, the second beam group can rest on the first group, creating two different levels on the floor.

Figure.(2.3.), utilizing CAD models, illustrates the assembling process of the building example. After positioning the columns (e.g. in pocket foundations) on the first floor, the first group of beams (dark grey) is placed, followed by the addition of the second group (light grey). Finally, the flooring elements are positioned, and the process is repeated for the second floor. The preparation of CAD files is crucial for this approach. In addition to displaying models and assembling ideas, preparing G-codes and water jet path planning is essential, allowing the designer to make necessary adjustments if issues arise.

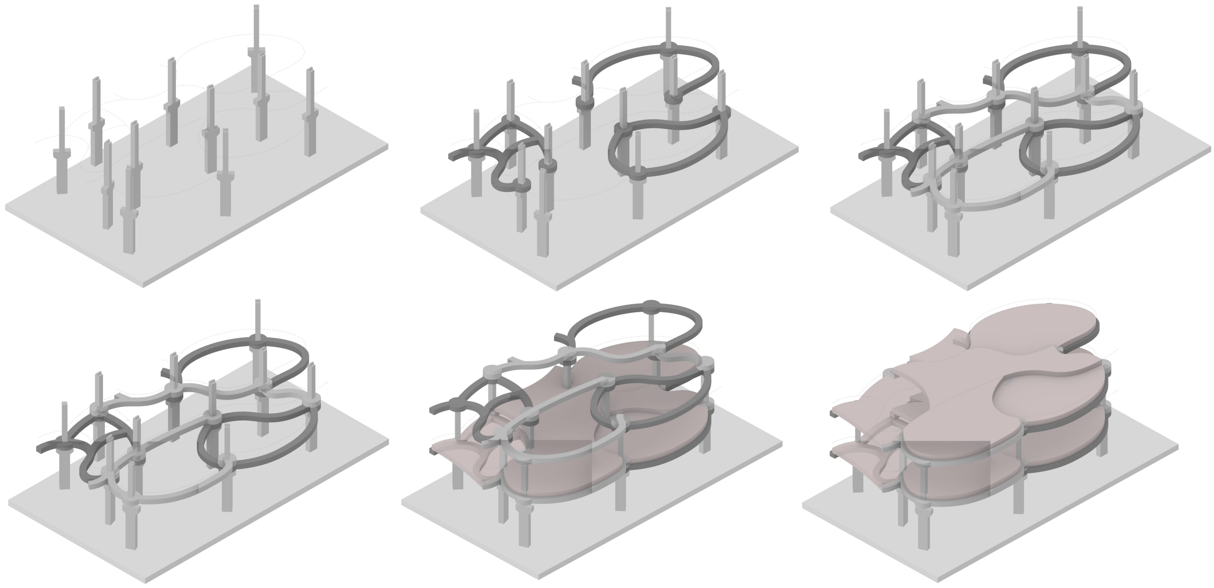

Figure 8: The assembling process of the building

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3. Conclusion:

Advancements in automated manufacturing methods and rising labour costs highlight the need for diversification in traditional construction techniques. This study focuses on innovative construction geometries achievable through a robotic WJCT with dry connections. Free-form elements can be constructed by utilizing water jet technology for element cutting. The study introduces dry connections achievable through water-jet technology and explores the implementation of a meta-heuristic algorithm to optimize the arrangement of curved beams. Additionally, it outlines the structural form, water-jet production process, and assembly scenarios for a two-story building. The efficient performance of the optimization algorithm, combined with the manufacturing and assembly of a scaled-down physical model, demonstrates the practical applications of the proposed optimized system.

Some highlighted results and out-look:

- Adapting the layout problem to optimize beam design yields efficient results, with Particle Swarm Optimization (PSO) successfully optimizing the layout in a two-dimensional searching area (x, y). - While using water jets to cut planar concrete elements eliminates formworks, concerns arise about concrete wastage when placing curved beams side by side. An algorithm optimizing beam placement considering these issues would be beneficial. - The complexity of predicting re-bar cages increases with beam curvature. Robotic production for re-bar cages is essential to manage individual forms efficiently. - Although limited to 2D geometries, WJCT offer diverse shape capabilities for elements and connections, which are valuable in construction details. - A limited number of joint types suffice to construct a complete building, simplifying assembly. - Thorough examination is crucial, considering complete beam layout, potential intersection points, and specifics related to re-bars and their manufacturing processes. - The presented assembly scenario ensures structural integrity, effectively transferring shear and bending forces while reducing bending in spans.

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