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The Jump Factory – reaching new heights in construction productivity

Introduction

The Jump Factory **(Figure 1)** is an innovative construction technique developed and implemented by Mace and consultants Davies Maguire to construct two residential towers in the East Village, London. This was in direct response to an industry shift towards off-site and modular construction, in order to address current and future challenges such as the housing crisis, labour shortages and construction's carbon footprint.

The intention was to replicate factory conditions on site, in order to construct the towers using modular and prefabricated elements, resulting in an improved programme, increased productivity and safety, and a reduction in the carbon footprint. The basic premise was to build a fully functioning factory, use the factory to construct a floor of the building, then once the floor was completed on a weekly cycle, jack the factory up and start again.

This paper describes the structural form of the factory, its support system and weekly lift cycle. It highlights the level of coordination achieved throughout the off-site works and discusses the measured benefits to programme, quality control, safety and sustainability targets. It also discusses the lessons learned from the factory operation and how it could be optimised for further use.

Concept

The key driver for the Jump Factory was to improve the programme for structure and envelope to a consistent one-week cycle to facilitate the following fitout trades. This provided an improvement of 2–3 days (approx. 30%) on the traditional concrete frame construction cycle of 7–8 days per floor, based on our experience of previous similar projects. The factory enclosure protects the workforce from adverse weather and also shields the gantry cranes, reducing production time lost.

A number of established construction techniques were considered in combination in the factory. Each of its significant elements used existing construction technologies: hydraulic jacks are commonly used to raise jump-form rigs for core construction; gantry cranes are widely used in factory environments; monorail technology is used in the installation of facades; and the efficient structural steel frame with a lightweight fabric wrap has been used on a number of temporary and permanent buildings. What was unique about the solution was the combination of these technologies.

FIGURE 1: Jump Factories in operation

The concept had been trialled previously, notably in Japan by a number of contractors. In 2003,Taylor *et al.*[1] captured the developments in automated construction in Japan at the time where it was primarily used for superstructure and envelopes. A similar method was employed by Ballast Nedam and BAM in 2012 to construct a concrete frame with a loadbearing facade at the Erasmus University Medical Centre in Rotterdam, the Netherlands.

The challenge at East Village was that the envelope was a non-structural, unitised cladding system fixed on the concrete frame. Traditionally, the concrete core proceeds first and is three levels ahead of the floor plate construction. This is followed by the envelope installation, which is approximately six levels below the working floors. The residential fitout therefore commences approximately 20 weeks behind the leading edge of the concrete construction.

The aim for East Village was to commence the fitout from the bottom of the factory and therefore just four weeks behind the leading edge of the construction.

Development phase

The Mace construction board gave approval for the methodology to be used on site in November 2015. Client buy-in was received shortly after on assurance that there would be no effects on the structure or architecture.

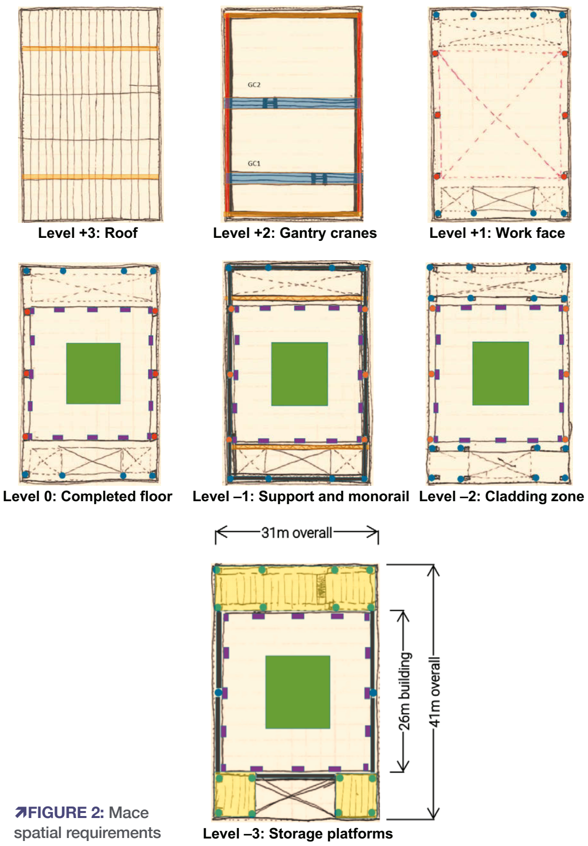
There followed a 12-month programme for the factories to be designed, fabricated and erected on site ready for the first jump above the retail areas at level 2. This was scheduled for November 2016.

Workshops started well in advance of fabrication. Mace assembled a specialist team comprising structural engineers (both permanent and temporary works), steelwork contractor, jacking and crane specialist Dorman Long and, most importantly, the subcontractors (frame contractor, MEP contractor and cladding contractor) who would be working in the factory.

Key to the success of the methodology was the input of all stakeholders, including the client, design team, supply chain, managers and operatives on site.

The workshops were split into three distinct threads to ensure that each group was focused on its particular responsibilities and able to move forwards with clarity.

The **factory design team**, comprising Mace, Davies Maguire, Dorman Long and Base Structures, considered the design and configuration of the factory and how this would work around the design of the permanent works without compromising the structure or architecture. This group met every two weeks, with specific tasks and outputs from the project team receiving Mace board approval in November 2015, until completion of the frame technical design in March 2016.


Level +3: Roof

Level +2: Gantry cranes

Level +1: Work face

Level 0: Completed floor

Level –1: Support and monorail

Level –2: Cladding zone

Level –3: Storage platforms

↗**FIGURE 2:** Mace spatial requirements

The **permanent works design team** was kept appraised of the progress on the design and specific interfaces with permanent structure on a monthly basis. This ensured that the structure, facade and architecture were not compromised by the design, in particular the impact of temporary static and dynamic loads on the concrete superstructure and foundations.

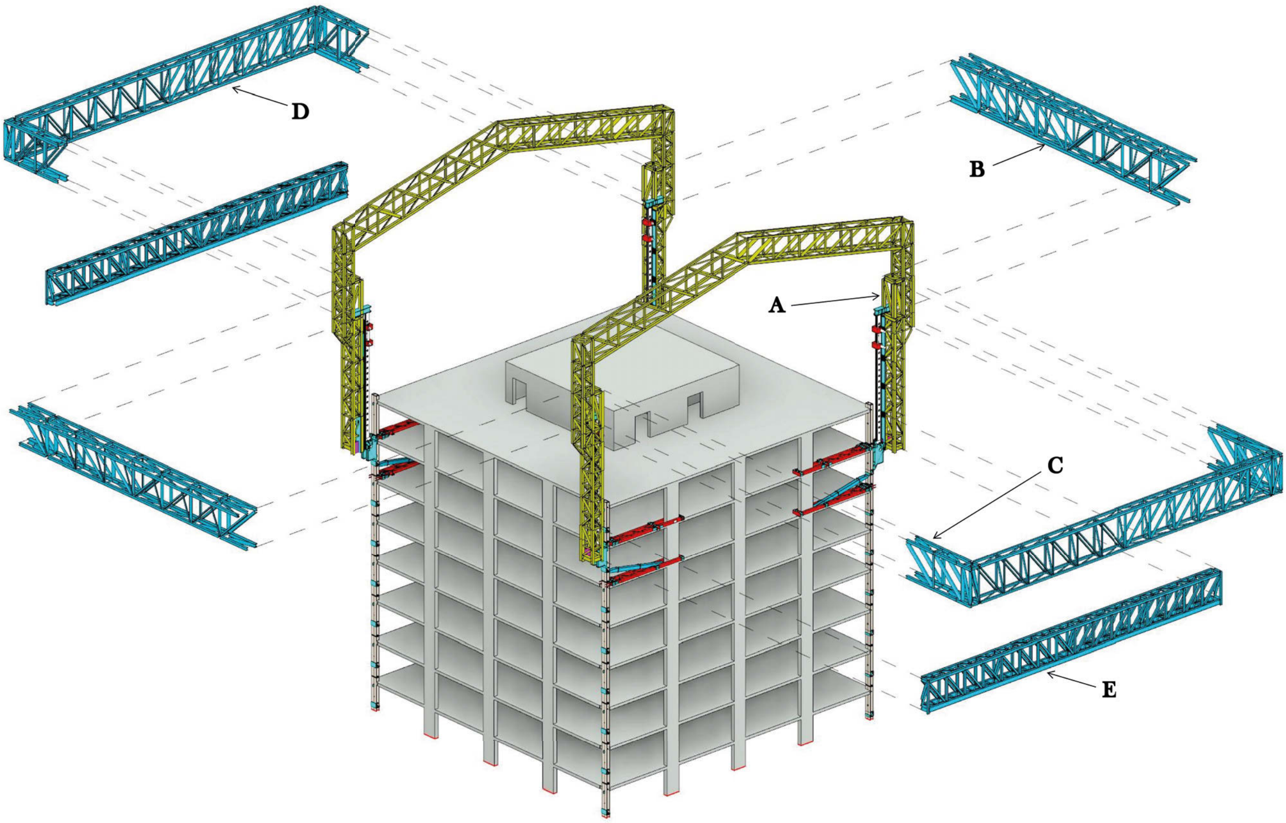
The main elements for the **supply chain** were engaged to understand key logistical challenges and ensure that the weekly cycle time could be achieved. This was primarily with the structure and facade contractor, but also involved the MEP contractor and fitout trades to ensure that their key issues could be incorporated.

The working groups provided the technical design, and agreed the construction cycle and key parameters at the end of March 2016. At this point, the structural steel fabrication subsidiary of Metal Yapi, a Turkish contractor which had already been engaged to carry out the facade manufacture and installation, was engaged on a design-and-build trade contract to develop the design and install the factories on site.

Design brief

The overarching requirement of the factory design brief was that the form of the factory should not dictate the form of the structure. The factory, like any other construction technique, was to facilitate the permanent works and not define them.

The concept of the factory was that of a steel trussed frame supported



↓**FIGURE 3:** Main components of factory off the building structure. The frame was to be fully clad and prevent water ingress. Inside were two gantry cranes: a main crane which lifted materials from the ground, and a slave crane which distributed them into place. A monorail running around the perimeter allowed cladding to be installed below the main deck. Hanging platforms were to be provided at levels below to enable access and act as loading platforms.

The key points of the spatial brief **(Figure 2)** were communicated to the structural engineers by diagrams summarising each level.

Structural development

Early discussions centred on how many supports would be provided, four or six, with the initial thoughts being for supports on six columns to spread the load. However, as the design of the truss system developed, it became apparent that the loads were concentrated at the corners, so the supports were limited to the four corner columns of the building.

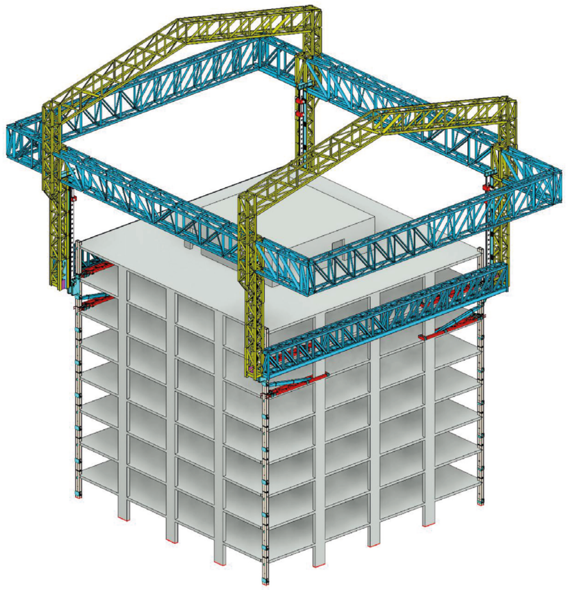
The basic requirement was that the factory and its trusses would only oversail the building footprint at roof level, so that the gantry cranes at the level below the roof would have unfettered access to the entire floor plate.

This led to the four trussed columns **(Figure 3 – A)** being supported off the innermost of their four legs so that the trusses framing into the columns would not clash with the building. The four columns were turned into two portal frames, as shown, to provide the main support to the factory roof, but also to provide stability in the transverse direction.

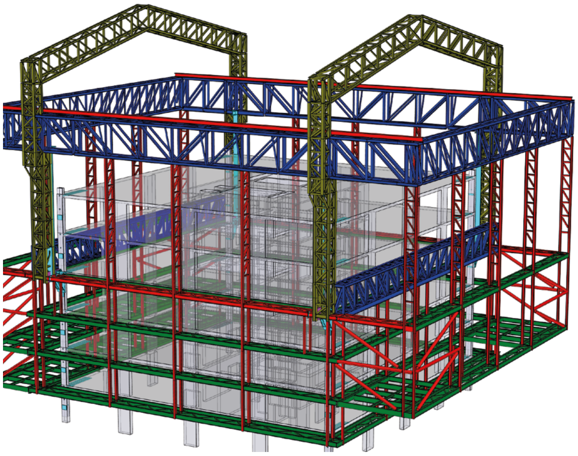
The column was cranked so that when the gantry support truss **(Fig. 3 – B)** was connected, the crane rail could run past the column. The gantry trusses cantilevered out from the other side of the columns **(Fig. 3 – C)** so the cranes could cover the entire internal footprint of the factory. Trusses **(Fig. 3 – B)** also formed portal frames with the columns to stabilise the factory in the longitudinal direction.

Trusses **(Fig. 3 – D)** stabilised the ends of the cantilevers, but mainly provided support to the hanging platforms below, and to the end enclosures to the factory up to the roof. Trusses **(Fig. 3 – E)** provided support to the internal edges of the hanging platforms. These were installed at a lower level so they wouldn't interfere with the functioning of the cranes. **Figure 4** shows the assembled main trusses.

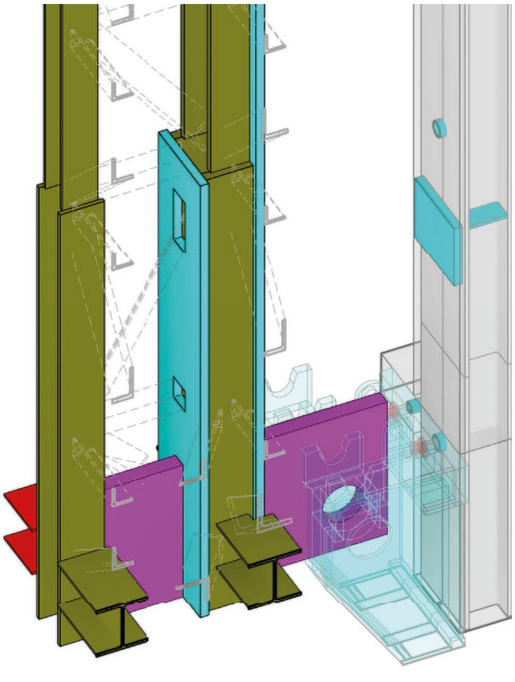
Figure 5 shows a work-in-progress model with the hanging walkways and platforms in place. It includes an option with an additional level, –4, but this was not constructed.



↗FIGURE 4: Assembled trusses



↗FIGURE 5: Work-in-progress 3D model



↗FIGURE 6: Column base

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>
> **A JACKING SYSTEM WAS DEVELOPED TO LIFT THE FACTORY**

The walkways at level –1 were braced to form a complete ring of horizontal trusses which carried the wind loads on the hanging elements back to the four support points. **Fig. 5** features the corner diagonals which carry the horizontal loads on the lower levels up to level –1.

Two of the legs at the base of each column carried a high-strength steel plate **(Figure 6)** through which the main support pins pass.

The pins were supported by fabricated steel brackets which, in turn, were picked up by the corner columns of the building **(Figure 7)**.

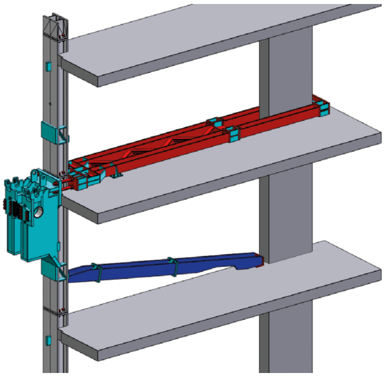
All base building columns, walls and slabs were of reinforced concrete, but the local loads and bending effects from these support brackets meant that the size of the corner concrete columns as originally designed was not adequate. However, twin UC 254 steel sections fitted within the profile of the original columns so these were used throughout **(Fig. 7)**.

To minimise the eccentricities on the columns, the brackets sat on 50mm wide bearing plates, which were working to their maximum stress levels to carry the 7000kN peak ultimate limit state (ULS) pin load. To carry the overall bending effects back to the main building, struts (dark blue) and ties (red) were provided.

Two sets of support brackets were provided, one above the other, and a jacking system was developed by Dorman Long **(Figure 8)** to lift the factory from one level to the next as part of its weekly cycle.

The structural analysis considered two separate phases of loading: the operation and jacking phases. The operation phase had over 600 load cases reflecting all the possible positions and loadings on the two cranes, in combination with the wind in any direction. Limits on the deflections, both horizontal and vertical, required for satisfactory crane performance proved the key criteria which governed the bulk of the member sizes.

The jacking phase had the cranes unloaded and 'parked'. The four jacks were linked together, but the advice from Dorman Long was that there could be slight differential movement between jacks during jacking. A differential movement of opposite corners of 50mm was therefore considered at serviceability



↑FIGURE 7: Support brackets

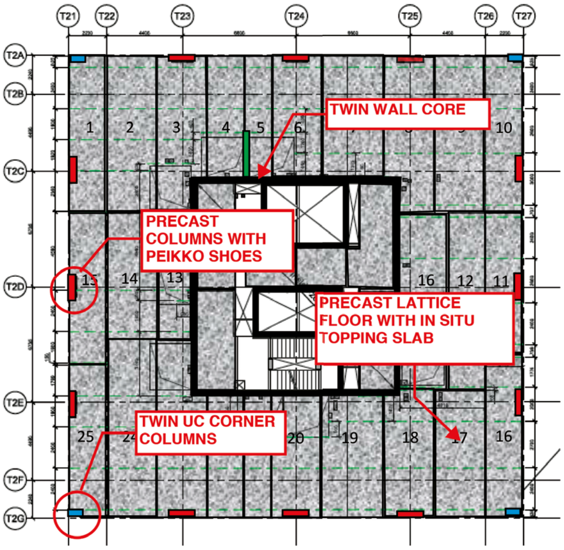
→FIGURE 8: Dorman Long jacking system

and ultimate limit states. A jack failure scenario was considered where one set of jacks in one corner could drop by the maximum stroke of 500mm. This was deemed to be an extreme case so was considered at ULS only.

Structural form of tower

The Jump Factory was created to facilitate modular and off-site construction. The 26- and 30-storey residential towers which it was used to construct were originally designed as conventional reinforced concrete structures. Parallel to the development of the factory concept was the redesign of the towers to a prefabricated form. The permanent works engineer worked alongside the precast contractor to develop an alternative, hybrid precast and *in situ* concrete structural solution to maximise the extent of off-site manufacture and increase productivity at site.

The resulting structure comprised a twin-wall core, the tallest in Europe, with a precast slab stitched together with an *in situ* concrete topping **(Figure 9)**. Precast plank sizes were optimised to facilitate ease of construction, with consideration given to practical sizes to lift and transport. The precast slabs also incorporated fire collars to suit the soil and vent pipes for the bathroom pod installation.



↖FIGURE 9: Components of tower floor plate

↖FIGURE 10: Twin-wall core with modular MEP ‘H-frame’

With the exception of the four steel corner columns, all other columns were precast and dimensionally similar to the *in situ* structural solution. The majority of the columns were manufactured as double-height elements to reduce the number of crane lifts on each floor cycle.

One of the big successes of the development, which significantly increased fitout speed, was the installation of vertical and horizontal services. This was in the form of prefabricated riser modules three storeys high and a horizontal ‘H-frame’ **(Figure 10)** – a prefabricated multiservice module dropped onto brackets on the twin-wall core before the slabs above were installed. Bathroom pods and utility cupboards were lifted directly into place by the gantry cranes.

Operation

Key to the success of the factory was an optimised logistical solution derived using lean planning of each operation to ensure that the weekly cycle could be achieved. All the trades needed to work together to ensure parallel activities were facilitated and the hook time for the crane optimised.

A dedicated logistics team ensured ‘just-in-time’ deliveries were achieved, which prevented double handling of elements. The result was an overall reduction in deliveries of 30% and it took just 13 minutes from a truck arriving on site to elements being lifted into place on the working deck **(Figure 11)**.

The weekly cycle for the floor plate is shown in **Figure 12**. This 55-hour cycle was designed to work within a Section 61 agreement for a construction site.

Initially, as with any new process, there were teething problems, as trades got to grip with their activities. However, after a few iterations, the cycles became progressively shorter, and at best a complete floor, with jacking, was achieved in under 35 hours.

Considering that three floors below, the cladding was installed, fully sealed and pressure tested and that dry trades could commence work, the programme savings were substantial. The repetitive nature of the floor plate and thus activities performed by operatives meant that efficiencies were achieved with replication. This also reduced the likelihood of accidents and improved quality.

Furthermore, with the use of loading platforms and internal gantry cranes, the factory operation was much less susceptible to ‘winding off’ than tower cranes, which can have a significant impact on the programme, especially over winter months.

Lifting of the factory was performed by four 250t Dorman Long hydraulic jacks at the corners (**Figure 13**). These were connected on a manifold to ensure the same lift rate.

The jacks, which were climbed out of the way during the weekly cycle to prevent damage, were lowered down and sat in a semi-circular cup on the upper bracket. Pins were locked through holes on the climbing bar, attached to the factory. Once this was done, a hydraulic arm removed the high-strength steel pin which was transferring the load onto the lower bracket.

The load was now carried onto the upper bracket, and lifting could commence. This was achieved progressively by stroking out the jacks in 500mm increments. Guide plates which sat in grooves within the climbing bar ensured that the vertical alignment was maintained for the next level.

When the factory was in the correct place, the pin was inserted through the upper bracket, transferring the load back off the jacks. The jacks were then disengaged and climbed back out of place. The entire process took less than an hour.

Before jacking, housekeeping and temporary works checks were completed. These were set out in an operations manual created and implemented specifically for the Jump Factories. This 'run book' ensured compliance with Mace temporary works procedures, BS 5975 and the Construction (Design and Management) Regulations. Only once all checks had been completed and countersigned was 'permission to jump' granted.

↘FIGURE 11: Gantry crane with twin 15t hoists to lift full precast sections to working face

Benefits, lessons learned and future iterations

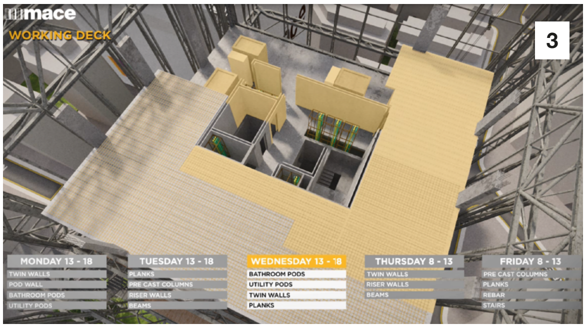
The implementation and operation of the Jump Factory achieved several construction firsts. This was particularly impressive considering that there was no mock-up and everything was achieved in its first iteration on site. At best during the height of operation, 18 floors were achieved in 18 weeks, representing a significant step change in productivity. This highlights that careful planning and the buy-in of all stakeholders, including the client, was key to the success of the factory.

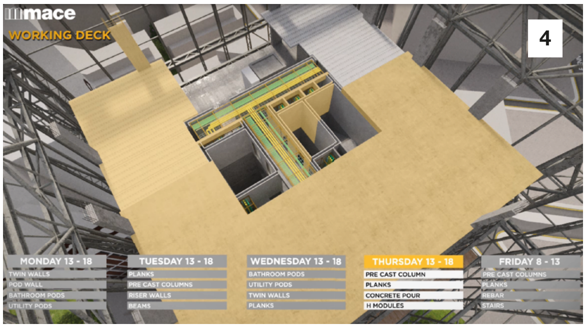
Key successes

The factory achieved its aim of facilitating modular off-site construction, which was demonstrated by regularly achieving the 55-hour cycle time. The integration of modular, prefabricated MEP components was hugely successful and reduced installation time. Installation of cladding three floors below the working deck provided a waterproof structure, meaning that follow-on trades could start considerably earlier than in a conventional build programme.

The factory was designed to operate in wind speeds of up to 40m/s. The ability to load out materials onto the deck or loading platform, with an enclosed slave crane for horizontal distribution, meant that winding off was rarely an issue.

↓↘FIGURE 12: Weekly floor cycle





Day 1 (Monday): Install steel columns and MEP risers and rear precast columns. Commence installation of twin-wall, pods and utility cupboards

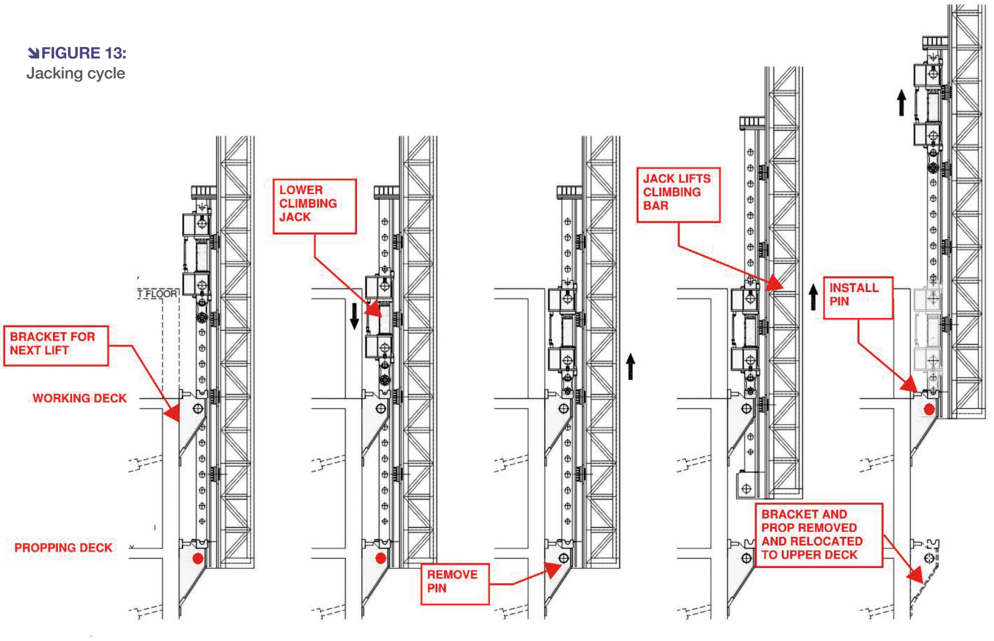
Day 2 (Tuesday): Install riser walls, front columns and propping for precast planks

Day 3 (Wednesday): Install twin-walls, H-modules and precast planks. Commence reinforcement fixing

Day 4 (Thursday): Complete twin-walls and H-modules. First concrete pour

Day 5 (Friday): Complete precast elements, install stairs, complete slab concreting, test facade, jack to next level

FIGURE 13: Jacking cycle



While improved productivity and reduced programme were major advantages, another significant plus was the health, safety and welfare benefits the factory provided. Working at height is still one of the biggest causes of fatalities and major injuries on a construction site. The factory, being a fully enclosed structure, removed a large part of this risk. For the facade team in particular, this risk was reduced by 96%, compared with conventional installation techniques. Flaps were installed on the lowest hanging deck to ensure materials and debris could not fall on to the site below.

On the working deck, the crane operator controlled the gantry cranes with a remote controller. The operator had full control of the deck and no lifts were done blind. This also meant that a crane operator did not need to climb a tower crane mast and thus removed risks associated with that, including lone working.

Just-in-time deliveries facilitated by a distribution centre meant reduced transportation into central London, thus decreasing pollution and reducing impact on neighbours. Modular and off-site construction reduced the amount of works on site, and the repetitive nature of these works meant a more streamlined process, an increase in quality and a reduction in risk.

A fully enclosed factory meant that it was protected from wind and rain, which prevented disruption of construction activities and created a better working environment for operatives.

As there was no resting rainwater, there was a significant reduction in the risk of slips, trips and falls on the working deck, as well as floors below. The weather protection also meant concreting could occur in all weather and was protected against frost.

Future developments

The form of the structure was well suited to workface factory operations; however, there was some redundancy in the trailing platforms and decks. The front loading platforms were well utilised, but the rear platforms, which were created to provide storage and welfare facilities, were rarely used. Streamlining and removing some of the hanging platforms would significantly reduce the weight of the factory and reduce installation and removal time by approximately four weeks.

Integration of the factory into the permanent works support system, by transferring the loads via brackets onto the tower columns, reduced the amount of lost cast-in fixings, but required constant removal and reinstatement of these temporary works. The 10-storey podium and wing buildings immediately adjacent to the towers meant that the factory could not be jacked back to ground on completion. Future uses of the factory will rely on the ability to lower its structure as close to ground level as possible to facilitate dismantling.

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Conclusion

The Jump Factory challenged conventional construction and has the potential to revolutionise the form of building in the future. It offers potential cost and programme savings, particularly on high-rise towers, supports sustainable development, and provides significant health, safety and welfare benefits.

The primary aim, to complete a floor cycle each week incorporating the structure and envelope, was successfully achieved over a period of 18 weeks. The methodology was also embraced by the MEP and fitout trades, who utilised the cranes and sealed working environment to maximise off-site manufacture and productivity. This was a unique and unexpected benefit, which is being developed for future projects.

Overall, the structural design of the factories, together with the jacking mechanism and craneage, provided a successful logistical solution for the construction of two high-rise residential towers using prefabricated components.

The innovative Jump Factory pushed the boundaries of conventional construction and represented a step change in construction productivity. Only by trialling new methods of construction will we be able to capitalise on historic lessons learned and help define the future of the industry.

FIGURE 14: View inside factory from working deck

REFERENCE

1) Taylor M., Wamuziri S. and Smith I. (2003) 'Automated construction in Japan', *Proc. ICE – Civ. Eng.*, 156 (1), pp. 34–41