Title:	**Modular Tall Building Design at Atlantic Yards B2**
Author:	David Farnsworth, Principal, Arup
Subjects:	Building Case Study Structural Engineering
Keywords:	Modular Construction Prefabrication
Publication Date:	2014
Original Publication:	CTBUH 2014 Shanghai Conference Proceedings
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Modular Tall Building Design at Atlantic Yards B2
大西洋广场B2 地块的模块式高层建筑设计

David Farnsworth

David Farnsworth

Arup
77 Water Street
New York, NY
United States of America 10007

tel (电话): +1 212.897.1316
email (电子邮箱): david.farnsworth@arup.com
www.arup.com

David Farnsworth is a Principal with Arup's New York office. His experience is both local and global and includes new mixed-use High-Rise tower developments, signature bridge designs, and various building, rail, airport and civil projects. Notable past and present projects include the Songdo Northeast Asia Trade tower in Korea, Marina Bay Sands hotel towers in Singapore, Beijing Z15 Tower, and China Resources Headquarters Tower in Shenzhen. He is currently focused on leading multidisciplinary design teams on complex projects in New York and around the world.

David Farnsworth是奥雅纳纽约办公室的负责人，经验丰富，曾参与过新型多功能超高层结构的设计，标志性桥梁的设计，和各式各样的建筑、铁路、机场和市政工程的设计。他在以往和近期所参与的卓著的项目包括：韩国的松岛东北亚贸易大厦，新加坡的滨海湾金沙酒店，北京的Z15大厦，深圳华润总部大楼等。目前，他致力于引领他的多专业设计团队参与纽约以至全球复杂项目的设计。

Abstract

The Atlantic Yards B2 Modular Residential Tower will be the tallest volumetric modular building in the world when completed in early 2015.

In January 2011, Forest City commissioned an integrated team of architects (SHoP), engineers (Arup), and construction specialists to develop a modular construction system suitable for a residential building that was being concurrently designed assuming conventional concrete flat-slab construction methods. The goal: develop a modular approach resulting in improved quality and cost savings compared to the conventional scheme.

The team developed a process and a modular system that maximizes work in the factory and minimizes work in the field. The system consists of modules that are shipped to site with structure, interior finishes, façades, and MEP systems complete. Connections between the modules have been designed to minimize the on-site workers' impact on the finished apartments.

Keywords: Modular Construction, Prefabrication, Tall Building, Atlantic Yards

摘要

预计于2015年初建成的位于大西洋广场B2地块的模块化住宅大楼将会成为世界上最高的大体量模块化建筑。

2011年1月，Forest市政府委任建筑师 (SHoP)、结构顾问 (奥雅纳) 和模块化顾问组成一个完整的团队来开发一种适合住宅类建筑的模块化施工体系，这种模块化施工体系同时也兼容传统的混凝土无梁楼盖的施工方法。项目目标为：开发出一种新型模块化结构体系——相比于传统的结构体系更能提高建造质量和节省建造经费。

设计团队提出了一种模块化体系和措施，最大化地将施工过程在工厂进行，尽量减少在现场施工。这种体系要求将在工厂完成的包含结构、内装修、幕墙和机电系统等的模块运到现场。将各设计好并排序的模块连接成一个整体，减小现场施工时对已完成的公寓的影响。

关键词：模块化施工，预制，高层结构，大西洋广场

Why Modular?

The Atlantic Yards development is envisioned to include 15 new residential towers with a total of 6,400 new apartment units, approximately half of which are affordable housing. The masterplan and land use agreement for the development was completed in 2006. With the onset of the financial crisis in 2008, the developer faced falling rents and rising construction costs. In addition, it had made commitments to bring the affordable housing online according to a set schedule, use union labor for construction, and spur economic development by creating jobs in Brooklyn. Under these circumstances, it was difficult to make the economics of conventional construction work.

In January 2011, a conventional reinforced concrete flat-slab framed building design was already underway. Given the

为什么采用模块形式？

太平洋广场开发的设想是包含15个新的住宅大厦，总数达到6400个新的公寓单元，大约总数的一半将作为经济适用房。总体规划设计和土地使用许可审批已于2006年完成。经历了2008年的全球金融危机，发展商面临着租赁价格跳水、建筑施工费用提高的压力。此外，根据固定的日程表，发展商已经承诺开始实施经济适用房的建设，雇佣工会劳动力，通过在布鲁克林创建就业机会来刺激经济的发展。在当时的大环境下，按传统的施工工艺进行施工将很难达到经济效益。

2011年1月，传统的钢筋混凝土无梁楼盖框架结构设计已经开始。介于考虑到以上提到的问题，业主决定雇佣一个顾问团队，对模块施工方法进行为期16周的项目调查研究。研究目标：开发出一种模块化的设计和提供相应的文件来与传统设计的竞标价格进行对比。

considerations noted above, the client decided to hire a team of consultants for a 16-week project investigating a modular approach. The goal: develop a modular design and a set of documents for price comparison against conventional bids.

SHoP Architects was the design architect for both the conventional and modular schemes. Arup was brought on board for structural, MEP, fire and life safety, acoustics, security, and IT engineering and consulting disciplines.

At the time, although modular construction had been used extensively in low-rise applications, there were few precedents for volumetric modular approaches for projects over 6 stories. The tallest was a 24-story apartment tower in Wolverhampton, UK. The challenge for the B2 modular design team was to develop a new modular construction methodology and system that was optimized for the construction market conditions in NYC, capable of withstanding the loads associated with going 32 stories tall, and would deliver quality with union labor at a price competitive with conventional flat-slab construction.

It is worth clarifying the difference between prefabrication and volumetric modular construction at this point. Various buildings, and many much taller than B2, have used prefabrication to varying degrees. Almost all tall buildings use curtain wall panels. Some use precast concrete. Modular construction is a style of prefabrication wherein complete portions of a building are assembled in a factory and delivered to site where they are assembled together to create a building. Generally, if the pre-assembled component has walls, floors, ceilings, and at least some of the finishes and services complete, then it is volumetric modular construction.

Project Basics

The B2 program consists of approximately 350,000 square feet [32,000 sq meters] of predominantly rental residential apartments. The tower massing is broken into 3 major "blocks", with a recess "reglet" between them to give scale to the building and avoid appearance of a monolithic extrusion. The reglets are accentuated by a combination of setbacks, cantilevers, and differences in façade (see Figure 1).

The ground floor consists of residential lobby and retail spaces, as well as the Dean Street entrance to the arena. A 90ft [27.5m] transfer girder spans over this arena entrance to support 19 stories of modules above. The substructure is constructed conventionally with reinforced concrete perimeter walls, base slab, and steel floor framing with slabs on metal deck. The sub-cellar level contains a locker room to support the arena; the cellar level is primarily filled with incoming utility service rooms and other central plant rooms.

The basic layout of the typical apartment floor plate follows the classic central double-loaded corridor bar type building typology (see Figure 2). Floors 12 through 32 are all residential apartments.

Modular Layout and Constraints

The basic floorplate is divided into modules that can be efficiently fabricated and fit out with systems and finishes prior to shipping to site. The largest floorplate has 36 modules per floor, generally arranged one on each side of the central corridor (which is included in the northern module). The building contains 930 modules in total. Studio apartments

SHoP建筑事务所同时承担传统设计和模块设计。奥雅纳 (Arup) 负责结构、机电、消防安全、声学、安保、计算机工程和顾问等专业设计工作。

在那个时候，尽管模块化施工方法已经广泛应用到低层建筑上，但是很少有先例应用到大体量、层数超过6层的建筑上。位于英国伍尔夫汉普顿的24层公寓大楼为当时应用此方法施工的最高建筑。B2地块的模块化设计团队面对的巨大挑战在于: 创建一种新的模块化施工方法，既能承担上部32层高的荷载分布，还能提供在完成质量和价格竞争上媲美工会劳力的传统的无梁楼盖施工方法的工艺来改善纽约市的建筑施工市场。

值得一提的是，工厂预制和大体量模块施工是不同的。各式各样的建筑，甚至是比B2还高的建筑结构都不同程度应用过工厂预制构件，几乎所有的高楼都应用幕墙墙板，而有些建筑采用预制混凝土幕墙墙板。模块施工是将建筑的一个小单元全部在工厂预制完成，然后运输到现场拼装，最终组建成完整的结构。概括来说，如果每个预制模块能包括墙、楼板、屋顶以及机电和简单的内装修等，这样的施工方式就是模块化施工。

Figure 1. The building massing is broken into 3 distinct building blocks with a recess and setbacks. (Source: SHoP Architects)
图1. 整个建筑物被划分成三块局部收进且形状不同的体块 (来源: SHoP 建筑)

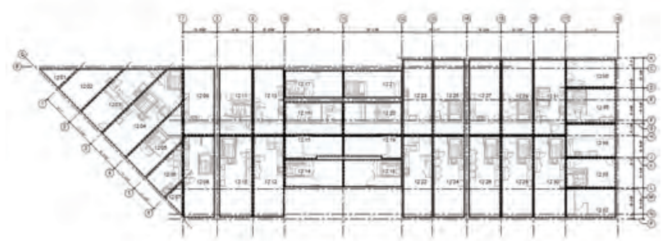

Figure 2. Typical modular floor plan with 36 modules per floor. (Source: Arup)
图2. 含有36个单元的标准层平面布置图 (来源: Arup)

Figure 3. Interior rendering of one-bedroom unit. (Source: SHoP Architects)
图3. 一房一厅单元的内部效果图 (来源: SHoP 建筑)

typically consist of one module, one-bedroom units two, and two-bedrooms three. The elevator core and stairwells are also constructed modularly, with the cabs and rails finally set and plumbed on site.

Transportation requirements limited the size of the individual modules. Typically, each fits within maximum dimensions of 15ft [4.5m] width, 50ft [15m] length, and 10.5ft [3.2m] height, allowing for "wide load" shipping on public roads. These limits work quite well for rental apartments, where living rooms are typically 13ft [4.0m] wide and bedrooms 11ft–12ft [3.4 -3.7m] wide. The interior layouts are such that the tenant might not know that the building was constructed with modular methods (see Figure 3). Although some modules approach 15ft [4.5m], the team kept them under 14ft [4.2m] when possible, as New York prohibits shipping of modules over 14' [4.2m] during rush-hour traffic.

Module size was also influenced by crane requirements. On B2, the tower crane had a 26.5 ton max lift capacity. Module weight ranges from approximately 7 tons for the smallest and lightest to 24 tons for the heaviest. Modules farthest from the crane were made smaller in order to fall within the specific lift limits at that crane radius. Modules closest to it are heaviest.

Building massing variation along the height, and the desire to have a wider range of unit types, resulted in 225 unique module structure types. With variations in piping and façade, many of the 930 modules are unique.

The project can be thought of more as a development of a process than the design of a specific module that will be stacked on great scale: mass customization rather than mass production. Details and methodologies are consistent, but each module is very much constructed to its own design.

Modular High-Rise Structural System

The building's base is constructed conventionally, with reinforced concrete basement slabs and perimeter walls, steel-framed cellar and ground floors, and a conventional steel-framed plinth level above the ground floor that provides a level platform on which to start stacking modules.

工程要素

B2地块计划主要包括近350,000平方英尺 (32,000平方米) 的出租住宅公寓。塔楼被分成三个主要"体块"，各"体块"之间添加凹陷的嵌条，给建筑以尺寸感，并且避免了外观上的整体溢出感。同时通过嵌条的内退、悬挑和配以不同的幕墙来突出建筑立面 (如图1)。

大楼一层包括了住宅大堂和一些零售空间，同时还包含迪恩街进入室内运动场的入口。入口上有一90 英尺 (27.5米) 跨度的转换梁支撑着上面19层的模块结构。地下室采用传统的钢筋混凝土外墙和底板，钢结构楼面梁和组合楼板。地下二层包含一个专为室内运动场准备的更衣间，地下一层主要用作市政管线设备房和中央机电设备用房。

建筑标准层遵循经典的内走廊的板式建筑形式 (如图2) 。从12层到32层全部为住宅公寓。

模块化布置和制约因素

标准楼层被分割成基本的模块，以便模块在工厂进行高效的加工预制，包括机电系统和一些内装修，最终运送到现场。最大的楼层每层有36个预制模块，通常每次均匀地在内走廊的两边放置一个模块 (同时包括北边的预制模块) 。整栋大楼一共包含930个预制模块，一室公寓采用一个模块，单卧室单元采用两个模块，双卧室单元采用三个模块。电梯筒和楼梯井也采用模块化施工，电缆和轨道最终在现场拼装和调整。

运输要求限制了单体模块的大小。一般来说，每个模块最大为15英尺 (4.5米) 宽，50英寸 (15米) 长，10.5英寸 (3.2米) 高 (能够在公共道路允许运输的最宽物品) 。由于出租公寓的客厅尺寸一般为13英寸 (4米) 宽，卧室尺寸一般为11~12英寸 (3.4~3.7米) 宽，所以运输要求对模块的限制并没有对公寓的尺寸造成较大影响。室内设计布局并不会让租客察觉到建筑是由模块化设计组装而成 (见图3) 。纽约交通规定，在繁忙时间段交通情况下的单模块最大运输尺寸不能超过14寸 (4.2米) ，所以尽管个别模块达到了15英寸 (4.5米) ，但我们的设计团队仍然尽量将模块的尺寸控制在14英寸 (4.2米) 以内。

除交通运输因素的影响外，模块尺寸也受到吊车要求的影响。在B2地块，塔吊只有26.5吨最大起重量。单个模块最大重量为24吨，最小重量为7吨。由于需要满足按塔吊半径的特殊起吊的限制，离塔吊越近可采用较重的模块。

由于建筑物形体沿高度变化，因此需求有的大量独特个体，于是产生了225个独特结构模块类型。加上管道及幕墙的变化，一共产生930个独立模块。

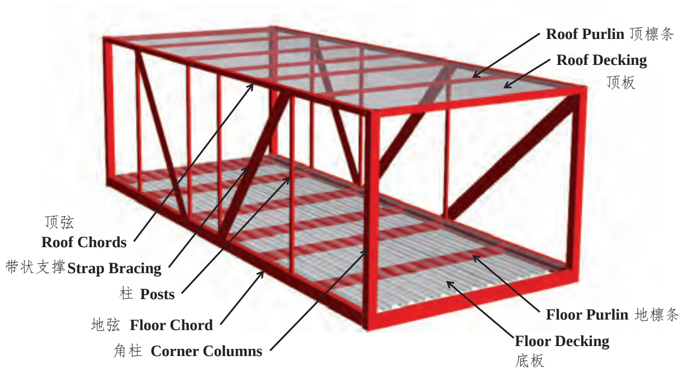

Figure 4. Module Chassis (Source: Arup) structural system. (Source: Arup)
图4. 单个模块箱体单元结构体系 (来源: Arup)

The basic building block of the modular system consists of a fully welded steel-framed chassis (see Figure 4). The side of the modules acts as a welded vierendeel truss spanning between corner columns, where the module columns below carry the weight of all modules above. The modular columns are typically 6″ [150mm] square tubes with plate thicknesses varying up to 1 ½″ [38mm] as built-up sections at the base of the tower. The module bottom chords are typically an 8″ by 4″ [200mm x 100mm] structural tube, the top chord is typically 4″ by 4″ [100mm x 100mm], and the intermediate posts are 2″ by 3″ [50mmx75mm]. At locations with walls along the side of the module, thin-gage diagonal strapping has been utilized to minimize deflections and steel weight. In other instances, hallways or doors must pass through the side of a module and the vierendeel panel must resist the shear without diagonal assistance.

The module floor system consists of 6″ by 3″ [150mm x 75mm] tube steel purlins supporting 2″ [50mm] metal deck running in the long direction of the module. A ¾″ [19mm] layer of cementitious particle board acts as the subfloor, and is followed by a ¼″ [5mm] layer of resilient acoustic padding and floor finishes (typically hardwood flooring) to complete the floor buildup. Each module has its own roof, with a 1″ [25mm] metal deck supported by 3″ [75mm] tube steel roof purlins. Two layers of 5/8″ [16mm] gypsum wall board are hung from the underside of the ceiling purlins to complete the ceiling assembly and provide membrane fire protection to the floor and ceiling members. The total floor–ceiling sandwich for the modular solution works out to be only 1′5″ [430mm]; clear ceiling heights of 8′6″ [2.59m] are achieved with a 9′11″ [3.02m] floor-to-floor spacing.

There is no concrete in the modules, making the system quite light relative to conventional flat-slab construction. On average, the modular solution weighs approximately 65% of a conventional RC flat-slab building. The significant reduction in superstructure weight was monetized as savings in foundation quantities and transfer steel.

Once the finished modules are shipped to site, they are stacked on the plinth and connected both vertically and laterally to adjacent modules. The roof of the modules acts as the lateral diaphragm and carries wind and seismic loads across the floor plate to a series of braced frames. Two braced frames are positioned in each primary direction and tied together at the roof level with a hat truss (see Figure 5). The modules carry their own gravity loads to the ground, but lateral loads are carried wholly by the conventional braced frames. The braced frames are primarily stiffness governed.

The building has a bi-directional set of two 100-ton tuned mass dampers to limit accelerations under wind events to the ISO criteria

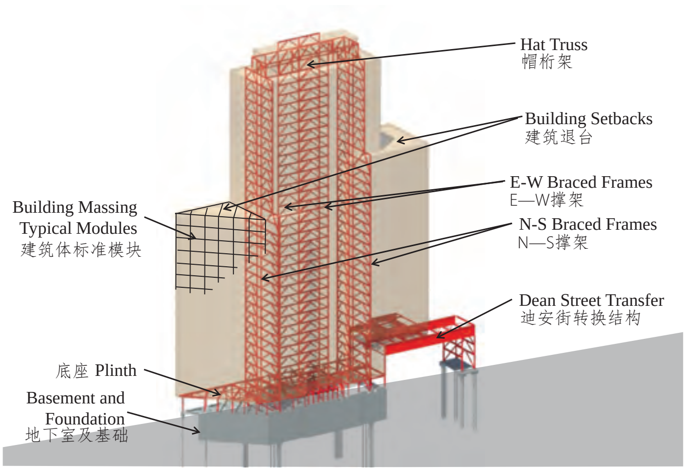

Figure 5. B2 Modular Structural System (Source: Arup)
图5. B2地块的模块结构体系 (来源: Arup)

本项目应被定位为一个生产过程的开发，而不是对个体模块的设计 (否则会陷入在大体量的困境中) : 定制化而不是量产化。始终如一的详图节点及设计理念，但每个模块都有独特的个体设计。

模块化的高层结构体系

建筑物底部采用常规结构: 钢筋混凝土底板和围墙，钢结构框架地下室及首层楼板，以及一个高于地面、采用常规钢框架的柱基座层，模块就搭建在钢框架柱基座层上。

模块系统的基座为一个完全焊接的钢框架底盘 (见图4) 。各模块的边框类似一个个焊接的矩形空腹桁架横跨在角柱之间，模块下部的柱承担了上部所有模块的重量。为于塔楼底部的典型模块的下柱为截面厚度为1½寸 (38毫米) 的6寸 (150毫米) 焊接方管。模块下弦杆典型截面为8寸x 4寸 (200毫米x 100毫米) 的结构方钢管，上弦杆典型截面为4寸x 4寸 (100毫米x 100毫米) 的结构方钢管，腹杆为2寸x 3寸 (50毫米x 75毫米) 的结构方钢管。沿着模块边缘的墙体，设置了薄壁对角拉杆来减小结构变形及用钢量。其他情况下，通道及门洞必须穿过模块边缘处，空腹桁架必须在没有对角拉杆的条件下来承受剪力。

模块的楼板体系由6寸x 3寸 (150毫米x 75毫米) 尺寸的管型檩条支撑2寸 (50毫米) 高的压型钢板组成，檩条沿模块长方向布置。一层3/4寸 (19毫米) 厚度的水泥基板作为楼面基层，在上面敷设一层1/4寸 (5毫米) 厚度的弹性隔音垫层以及楼面完成面 (一般为硬木地板) 组成了完整楼面。每个模块都设有独自的屋顶，屋顶由一块1寸 (25毫米) 厚的压型钢板及3寸 (75毫米) 高的方钢管檩条组成。两层5/8寸 (16毫米) 厚的防火石膏墙板由吊在屋顶檩条下组成天花板并给天花板及地板钢构件提供防火保护。由于模块的楼板加吊顶层的总厚度为1英尺5寸 (430毫米) ，在层高为9英尺11寸 (3.02米) 的情况下建筑净高可达到8英寸6寸 (2.59米) 。

模块中不包含任何混凝土构件，这样的楼板体系对比相同情况下的混凝土无梁楼板体系要轻。平均下来，本模块体系的重量只相当于相同情况下混凝土无梁楼板体系建筑的65%。上部结构重量的大大减轻将大大减少基础用量及转换钢结构。

当模块运抵工地时，工人们会立刻开始将模块组装至基座并将相邻模块进行竖向及水平向连接。模块的顶板作为水平向刚性楼板将风载荷及地震荷载传递至竖向支撑框架。两片支撑框架分别放置在两个主方向上，并在屋顶层由一个帽桁架连接在一起 (见图5) 。模块能够将自身重量传递至底面，但水平向荷载完全由支撑框架承担。支撑框架尺寸主要由刚度控制。

本项目设有一组两个100吨的双向质量调谐阻尼器来限制风荷载下的加速度，以满足ISO规范规定的住宅类建筑在风荷载作用下的最大加速度要求。虽然质量调谐阻尼器在只有32层高建筑中并不常见，但由于模块系统的重量轻，加上建筑物的方向以及质量集中在角部的特点，采用施加阻尼来控制加速度及满足规范要求的居住者舒适度是最有效经济的方式。轻质量建筑物的益处使得仅采用增加2组100吨质量调谐阻尼器即可得到大量的有效阻尼 (包括扭转在内的全方向上增加5.0~6.0%) 。结构的在X，Y双向及扭转作用下的10年重现期下的加速度可降至14.9 milli-g。

虽然最初的设计方案考虑模块围绕钢筋混凝土核心筒摆放，但是全钢结构被公认为最优方案。原因就在于钢结构方案令施工场地上的技工数目最小化，并提高系统内各部分的兼容性。相对于纯钢结构，混凝土结构的长期变形的特质使得两个不同结构体系的连接非常复杂。在钢结构方案中，单独一个承包商就能够对模块的建造及钢支撑框架的外形控制负责。相连接并堆叠在一起的模块在使用工况下可以保持稳定，而不需要钢支撑框架的帮助。大量的柱子及模块间最小设缝宽度也为结构提供了足够的冗余度，

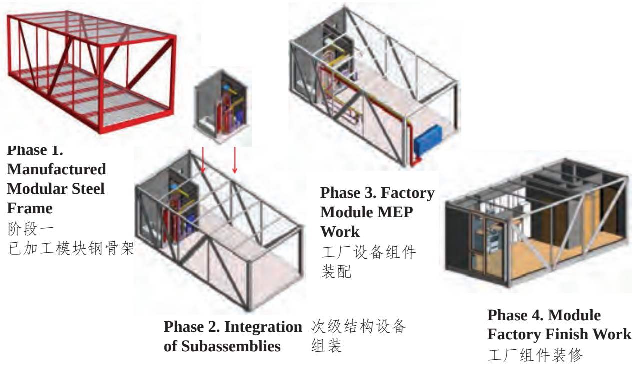

Figure 6. Fabrication phasing. (Source: Arup)
图6. 模块的生产流程 (来源: Arup)

Figure 7. Module chassis arrives to factory for fitout (Source: Arup)
图7. 模块箱体单元运送至工厂进行内装 (来源: Arup)

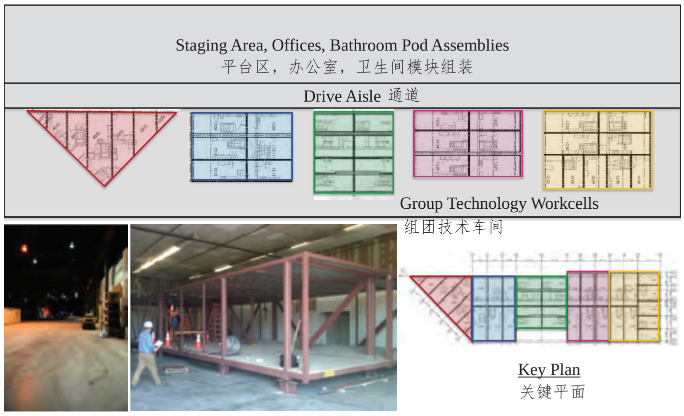

Figure 8. Factory layout. (Source: Arup)
图8. 安装厂布置 (来源: Arup)

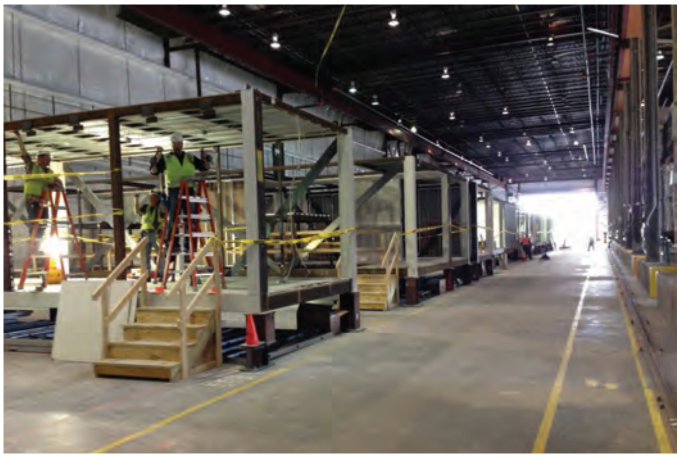

Figure 9. Modules on pedestals in factory for fit-out. (Source: Arup)
图9. 模块箱体单元结构置于支座上进行内装 (来源: Arup)

for residences. While TMD's are not very common for buildings of only 32 stories, the low mass of the modular system, in combination with building orientation and an acute cornered massing, resulted in baseline accelerations such that adding damping proved to be the most cost-effective means of controlling accelerations and achieving occupant comfort criteria. The benefit of the low mass of the building meant that significant supplemental damping (~+5.0 – 6.0% in all directions including torsion) could be achieved with only 2-100 ton TMD's. 10 year accelerations at the worst point on the building combining both x, y, and torsional effects are now at expected to be at 14.9 milli-g.

Although a reinforced concrete core design with steel modules placed around the core was initially considered, the steel-only solution was deemed superior in order to minimize the number of trades on site and ensure compatible tolerances between all systems. The long-term deflection characteristics of concrete relative to steel would have made connection of the two disparate systems complicated. In the steel-only option, a single subcontractor can be responsible for geometric control of both the module fabrication and conventional steel-braced frame erection. The stacked and connected modules are capable to maintain stability under service conditions without the assistance of the braced frames. The sheer number of columns and minimal gaps between modules also ensures a very redundant load path should any single module column be lost. Tension connections between module columns have been designed in accordance with NYC integrity provisions to further enhance resistance against progressive collapse.

The decision to use the module roof as the diaphragm was based on the project maxim of finishing as much of the apartment in the factory as possible and minimizing potential for on-site activities to damage the finished apartments. With the roof acting as diaphragm, the primary structural connections between the modules can be done from outside the apartment units, avoiding the risk of doing heavy steelwork in a finished apartment. This proved to be one of the keys to the phasing puzzle.

Module Fabrication and Fit-Out

Steel Fabrication

The module chassis are fabricated at Banker Steel in Virginia. A series of three-dimensional jigs are used with setting pins to ensure tight geometric control. The long sides of the modules are welded together first; floor purlins are connected to complete the box. Lastly, the metal deck floor and roof are pinned to the purlins and the ¾" cementitious particle board subfloor installed.

任何一根柱子的失效都不会导致结构失稳。模块间柱子的抗拉连接已经完全依照纽约规范提供的抗连续倒塌的要求进行了设计。

利用模块顶板作为刚性隔板的决定基于最大化工厂组装及最小化现场施工预防对已完工模块的破坏的原则。由于利用模块顶板作为刚性隔板，模块间主要的结构连接能够在公寓单元的外层完成，避免了在成品公寓内部进行大量钢结构施工所带来的风险。这就为模块拼接提供了一个重要因素。

At this point, the modules are loaded onto a truck for shipment to FCS' Brooklyn factory for fit-out. The crane pick points on the modules utilize a lifting lug designed to bolt down to the same connection angles that are used onsite to bolt the modules together.

Module Fit-Out Work in the Factory

The factory follows a multi-step process to maximize fabrication and fit-out efficiency (see Figure 6). The module frames arrive at the FCS Modular factory in the Brooklyn Navy Yard and are typically stored until the prior floor module's fit-out work is complete (see Figure 7). When the factory is ready for the module frames, they are brought into the factory via a reach stacker, and an overhead gantry crane or wheel lift is used to transport them to the work areas. The work areas, called "group technology workcells", consist of a group of 6 to 8 modules placed adjacent to each other in a geometry that matches exactly the positioning of the modules on site (see Figure 8) so that workers can visually align finishes and systems across module matelines. The geometric controls for the pedestals in the factory use the same setting pins that match both the geometry of the steel fabricator's jigs and the final setting pins used in the connections on site. This ensures that module frames have met the required tolerances and all fit-out work can be performed with confidence.

The project approach gains efficiencies by maximizing prefabrication and pre-assembly. By the time the module frame shows up at the factory, a number of pre-assembled kits, ranging from wall frames to full bathroom pods, will be ready for immediate installation in the module.

Wall panels and ceiling gyp boards are placed first (see Figure 9). Light-gage stud-framed wall panels are placed between posts, supporting two layers of 5/8" gypsum wallboard on each side of the module. When combined with the equivalent wall or floor on the adjacent module, the module perimeter walls, ceilings, and floors provide both the required fire separation between apartments and the membrane fire protection for the module steel members.

When the perimeter walls and ceilings are complete, the pre-assembled bathroom pod (see Figure 10), complete with tiling, fixtures, plumbing, wiring, etc, is inserted. This greatly reduces the time required to complete the module, as the nature of the wet work and complex plumbing inherent in the bathroom pods require more time to produce than other finishes.

The MEP systems are arranged such that vertical risers service each stack of modules with all sanitary drain and vent piping, hot and cold potable

Figure 10. Framing, fixtures, and plumbing installed in bathroom pod. (Source: Arup)
图10. 在浴室内的框架、结构及管道的安装 (来源: Arup)

模块制造和装备

钢结构制造

模块的底盘是在弗吉尼亚州的Banker Steel 中制造的。其中，严格的几何控制是通过一系列的定位销和三维夹具来实现的。首先把模块的长边焊接在一起，然后将楼板的檩条连接起来形成一个，最后将压型钢板楼面和屋盖与檩条铰接，再安装水泥基底板。

此时，将模块装上卡车运送到FCS' Brooklyn工厂装配。模块上的起重吊耳被设计成与连接件相同的连接角度，可供在工地将模块组合在一起。

工厂中模块的拼装|

该工厂根据多步骤的程序来最大程度的提高制造和装配效率 (图6)。模块框架到达在布鲁克林海军造船厂的FCS模块化工厂并被保存，直到模块内装修的装配工作完成 (图7)。当工厂已经准备好处理模块框架时，模块框架就通过前移式堆带送进工厂并且用高架龙门起重机或者轮式铲车将它们送入工作区。工作区，也叫"成组工作单元"，由一组6到8个相邻放置的模块组成，它们的定位与在工地的模块几何位置相一致 (图8)，因此工人可以直观地通过模块的基准线来调整完成面和结构系统。基座的几何控制方法也大致相同，使用了定位销，将钢结构制造的夹具和最后在工地使用的连接部位的定位销互相吻合。这确保了模块框架满足了允许误差，并且所有的装配工作可以继续进行。

该项目通过最大化预制和预装备来获得效率。当模块框架运抵工厂后，一些预组装的套件 (从墙框架到卫生间) 将立刻被安装在模块中。

墙板和吊顶石膏首先放置 (图9)。轻质框架墙板被放置在立柱之间，支撑位于模块各个边的两层16毫米厚石膏板墙体。当与在相邻模块上的墙和楼板组合时，模块周边的墙、天花板和楼板提供了公寓间的防火隔离和钢构件的防火保护层。

当边墙和天花板都完成后，含有瓷砖、灯具、水管和电线等等的预装配的卫生间 (图10) 就可以安装了。由于卫生间中防水保护工作和复杂的管道连接工作的特性，一般卫生间安装要比其它地方的完成面的施工需要花费更多的时间，这种施工工艺将大大减少完成模块的时间。

在每一批模块上安置建筑设备 (MEP) 系统，其中含有所有的卫生排水和排气管道，冷热饮用水和采暖热水，它们通常位于卫生间，这样立管就可以贴着中央走廊以便工人从那里进入来完成工厂中未完成的管线连接工作 (图11)。

Figure 11. Completed bathroom in factory with accessible pipe riser backing into central corridor for access to make mateline connections in the field. (Source: Arup)
图11. 工厂内制作完成的浴室，竖向管道井均穿越楼板至中心走廊，保证在工地上可进行连接 (来源: Arup)

Figure 12. Module ready for shipment to site with weather protection and façades installed. (Source: Arup)
图12. 包裹有防水保护膜和幕墙的模块单元等待运至施工场地 (来源: Arup)

water, and heating hot water, located typically as part of the bathroom pod and placed so that the riser backs up to the central corridor, where it can be accessed for site connections from the one area in the module that won't be finished to completion in the factory (see Figure 11).

In conventional construction, architects and MEP designers typically locate bathrooms back to back so that a shared riser can be used. In modular construction, it pays to break this rule so that the riser can be accessible from an area that is less time-consuming to fit out in the field. If the risers were shared, the finished bathroom would require a leave-out in the tiling to allow for field access to the riser to make the connections. The money saved on the single riser is wasted on the field labor needed to redo the time-intensive tiling work.

Once the perimeter walls and bathroom pods are installed, the MEP systems branch out from the riser at the bathroom pod to service the rest of the apartment. A packaged terminal air conditioning unit is installed in the façade and serviced with electric power for cooling and boiler hot water for heating.

Each apartment is wired to a single apartment panel. There will be a set of circuits for each module in a multi-module apartment. "Quick-connect" plug systems are used to connect the circuits in the adjacent modules to the module with the apartment panel. "Home-run" wiring is precut and coiled for shipment in the module for the connection back to the central meter room, which will be completed when the module is set on site.

Prefabricated curtain wall panels are also installed on the modules in the factory. These panels are prefabricated at MG McGrath in Minneapolis and shipped to the FCS factory in Brooklyn, where they are attached to the module with high precision. A compression gasket is fitted all around the perimeter of the curtain wall and compressed to form a seal when set next to and on top of the adjacent modules.

Once the apartment finishes are completed in the factory, each module is weatherproofed for shipment to site with an EPDM roof membrane at every module level and a perimeter Tyvek vapor barrier (see Figure 12). The wheel lift brings the modules from the group technology work cells to a storage area outside the factory where the modules will await shipment to site.

Site Erection

As the small site can store only enough two or three modules at a time, modules are effectively delivered "just in time" — making the close proximity of factory and job site critical. Two stories of braced frame are erected in advance of the module erection. The braced frames are prefabricated so that only minimal bolting is required on site. The

Figure 13. Module erection on site. (Source: FCRC EarthCam)
图13. 模块单元现场吊装 (来源: FCRC EarthCam)

在传统的施工中，建筑师和MEP设计人员通常将浴室背靠背的放置，因此就可以共享立管。在模块化的施工中，打破了这项传统，立管被放置在更加容易接触的区域，以减少现场装配所消耗的时间。如果共享立管，完成的洗手间就需要留出一个未铺瓷砖的空间来提供立管连接。这样，由共享立管省下的钱又会浪费在工地上很耗时和费钱的贴砖工作中。

一旦墙面和洗手间装配好，MEP系统就从洗手间的立管中分离出来被用于公寓中的其它部分。空调终端单元安装在立面中，由电制冷和利用锅炉热水来制暖。

每间公寓都连接到一个单独的公寓面板。在多模块的公寓中，将有一组电路供给各个模块并使用"快接"插头系统来连接相邻模块的电路到设有公寓主面板的模块。"主面板"线路被预切并盘绕在模块中以方便运输，这些线路会在工地装配时被连接到中央控制房。

预制幕墙板也会安装在模块上。这些面板是在明尼阿波利斯的MG McGrath工厂中预制的并且运送到位于布鲁克林的FCS工厂。在那里，这些面板会被精确地安装到模块上。一个压缩垫片会贴在整个幕墙的周围，一旦和相邻模块对接，压缩垫片就会形成密封的作用。

当公寓的内装修在工厂中完成，每一个模块都在EPDM屋盖膜和外围的Tyvek气密防风雨的外罩下送往工地 (图12) 。模块通过轮式铲车从成组工作单元中运送到一个工厂外的储藏区域，等待被运送到工地。

工地上的安装

由于工地较小，每次只能储存两个或者三个模块。模块必须及时运送到安装现场，这样就使得工厂和工地必须临近。带有斜撑的两层框架应在模块架设前就安装好。带斜撑的框架是预制的，因此在工地上螺栓的安装工作量会降到最小。位于中间走廊上方的带有连系梁的中央"梯子"在工厂中焊接好并单独运送，以方便在工地架设。当模块到达工地后，一个单独的塔吊将它吊起并放在准确的位置，通过定位销和下面的模块相连，这样就能控制当前

central "ladder" section with the link beam over the central hallway is welded in the shop and shipped as a single piece for easy erection in the field. When the module arrives on site, a single tower crane lifts it into position and places it on setting pins attached to the module below, which control the geometry of the current set. The module can then be taken off the hook (see Figure 13). The roofs of the modules on the level below provide a safe work platform for the steel workers, who handle the guide ropes and ensure that the module is placed correctly. After a number of modules are set, workers walk across the roofs and install the mateline bolted connection plates that tie the modules together and back to the braced frames.

At the time of this writing, only six modules are being erected per day. Factory production rates rather than erection speed have proven to be the limiting factor. The actual lift process can take as little as 10 minutes per module. Considering trucking restrictions, delivery logistics, and rigging, it would be entirely feasible to erect 12 modules and associated braced frames in a normal workday. With 36 modules per floor, this could equate to a floor every three days!

Mateline Work
A few floors below the active structural erection, carpenters and MEP trades are working through the modules to connect up the MEP risers, link the apartment electrical systems to the electrical bus duct riser located in the central core area, and splice together the sprinkler system. Once the MEP systems are connected, workers will complete the architectural finishes at the mateline areas and ensure the fire protection membranes are complete.

Benefits

More of a process than a product, the modular system designed for Atlantic Yards B2 is versatile enough to be employed on a wide variety of projects. Modular construction can provide significant advantages over conventional construction in terms of worker safety, neighborhood impact, consistent workplace location, and productivity in all weather conditions.

Closing Statement

This design and construction methodology is likely to play a significant part in the future of tall buildings and vertical urbanism. Driven by cost and schedule pressures and enabled by technological advances and labor cost differentials, modular construction is likely to prove an important tool for housing the world's increasing urban populations.

模块的几何位置，模块然后就能从吊钩上取下 (图13) 。下层模块的屋盖为钢结构工人提供了一个安全的工作平台来调整模块，将其安置在正确的位置。在一些模块安置好后，工人行走在屋顶上并安装螺栓连接板来使得模块连接在一起并与支撑框架相连。

在本文写作的时候，每天只有六个单元可以完成安装。安装速度是受制于工厂的生产速度。每个单元实际的吊装过程可能只需要十分钟，在考虑了运输工具能力、物流发货速度和索具各方面的限制后，在一个工作日内完成12个模块和相关的支撑框架系统的施工是完全可行的。由于每层仅有36个构件，完成一层仅需要3天时间!

模块连接工作
结构体系吊装完成后，木工及管道工可迅速完成以下几层模块的机电管道竖向连接，将该公寓的电气系统连接至中央电气系统，并连接自动喷淋灭火系统的接头。一旦机电管道系统连接完成后，施工人员将在联通区域完成建筑防火面层。

优点

此种方法更像一个流程而不仅是一件产品，为大西洋广场B2地块设计的模块化系统的布置非常灵活，能在各种项目中应用。模块化施工的优势在于它能比常规施工方法更好地保护施工工人安全，减小对周边环境影响，适应紧凑的施工场地以及适应不同天气条件。

综述

这种设计及施工方法可能会在高层建筑和垂直城市化的未来发展中起到重要作用，受成本控制及进度压力的驱动，通过技术进步以及劳动力的差异化运用，模块化施工可能会被证明是满足日益增加人口的住房需求的有效措施。