THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Chinese National Engineering Research Centre
For Steel Construction (Hong Kong Branch)
國家鋼結構工程技術研究中心香港分中心

Technical Seminar on Modular Integrated Construction (MiC)

# Key Considerations for Modular Integrated Construction in Hong Kong

K.F. Chung and T.M. Chan

# CNERC for Steel Construction (Hong Kong Branch)

**Development Bureau of Government of Hong Kong SAR**
**Construction Industry Council**
**Chinese Iron and Steel Association**
**Chinese Steel Construction Society**
**Chinese Constructional Metal Structures Association**

***Promoting***
***sustainable infrastructure development***
***in Hong Kong***

***Promoting***
***export of Hong Kong and Chinese Steel Construction Industry***

***Promoting***
***advanced structural engineering technology***
***In modern steel construction***

Collaborators

Imperial College London, Institution of Structural Engineers, the Steel Construction Institute, Tsinghua University, Tongji University, University of Science and Technology Beijing.

# Development of Hong Kong Construction Industry

Development Bureau

Construction Industry Council

CNERC

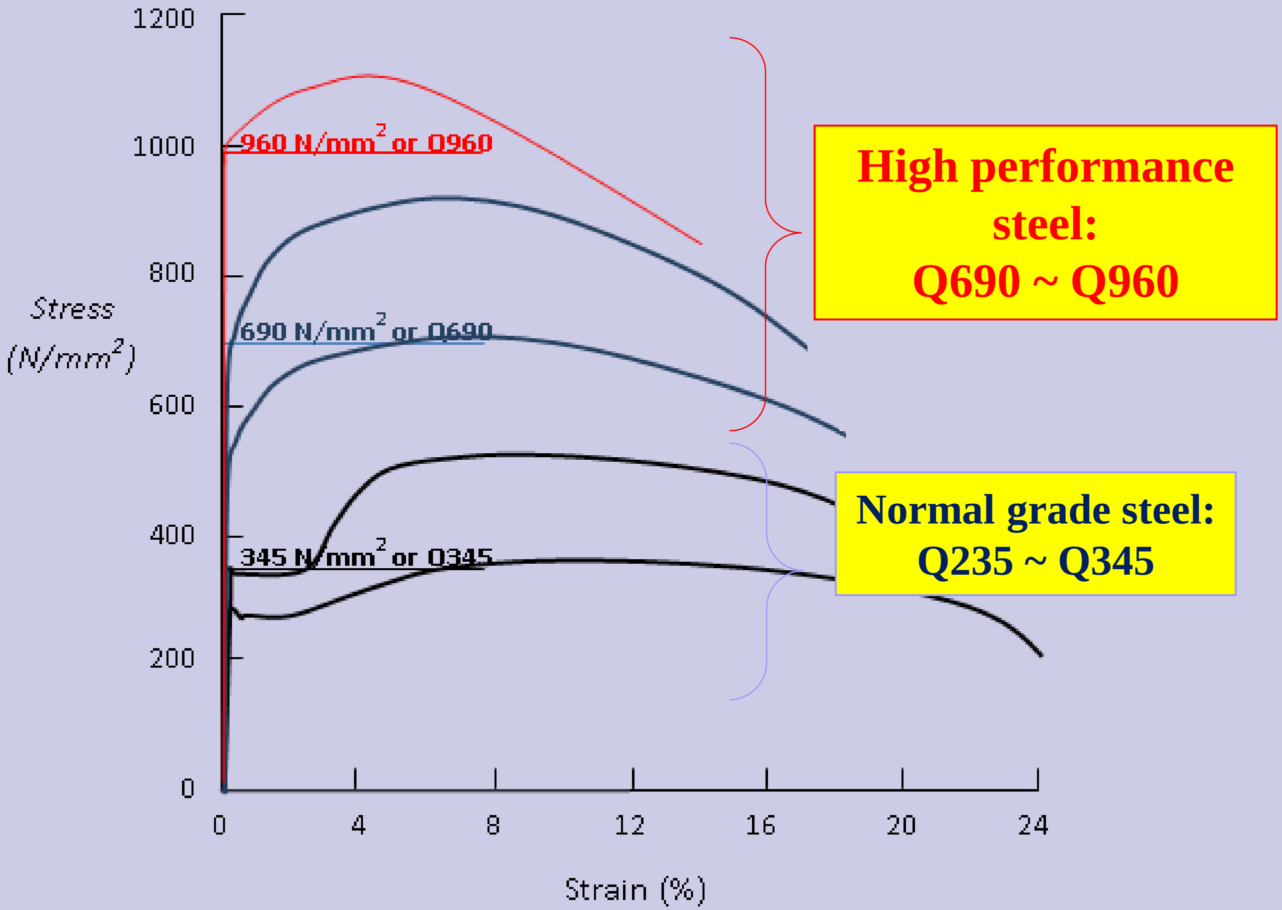
Hong Kong Construction Industry

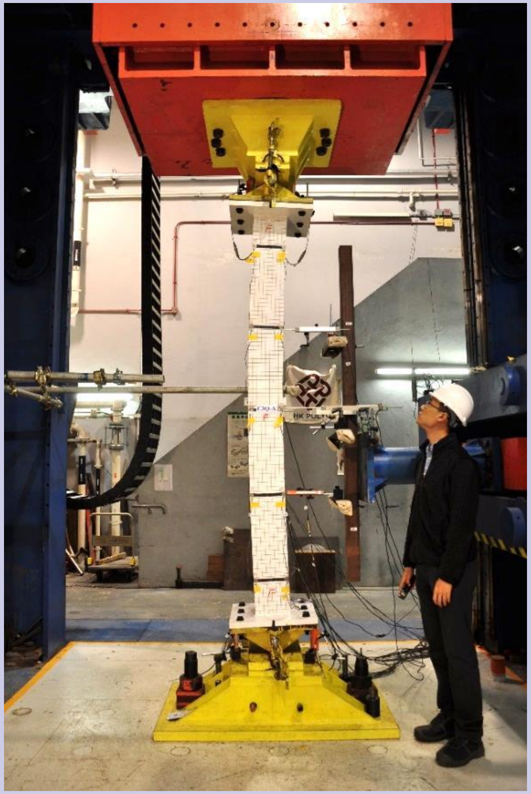
International Design Centre for Infrastructure Development

Chinese Steel Construction Industry

International Construction Centre for Infrastructure Development

# Structural efficiency of building structures - Effective design and construction using high performance steel



# Challenges for Hong Kong Construction Industry

- Construction productivity, site safety and quality.
- Demand of workforce, aging of skilled labour, lack of young people.

# Challenges for Hong Kong Construction Industry

## Self weight of modules

- Normal weight concrete, light weight concrete
- Steel module, concrete module and hybrid module

## Connections between modules

- Strength, stiffness and buildability

## Load carrying capacities of columns

- 3 storeys, 20 storeys and 40 storeys

## Progressive collapse

- Structural integrity against accidental loads

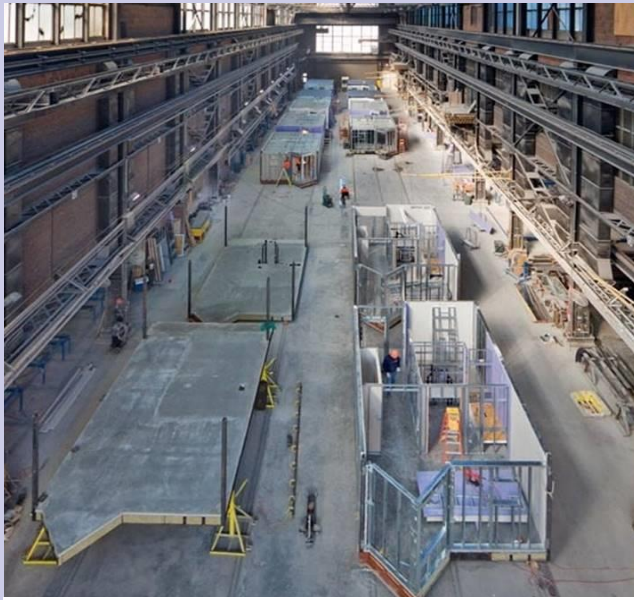
New construction forms require new materials and new design.

***Explorative research for innovative applications !***

# Hong Kong Modular Integrated Construction (MiC) Innovations

Innovation and Technology Commission
The Government of the Hong Kong Special Administrative Region

NAMI



Manufacturing of fully furnished modular units in shop

Construction of high-rise buildings using modular units on site

Project Sum: **HK$26 M** with 25% financial support from industrial collaborators

***July 2019 to June 2021***

# Hong Kong Modular Integrated Construction (MiC) Innovations

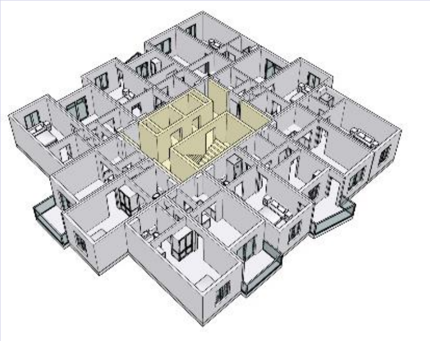
## ITF Project by NAMI and CNERC-Steel

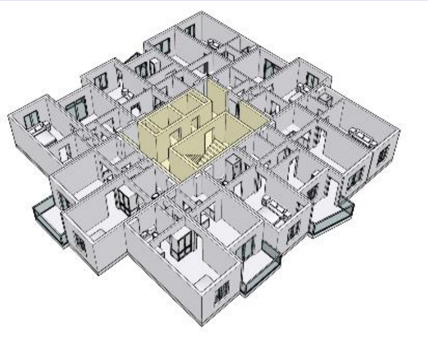
**Challenges to adopt MiC in Hong Kong**

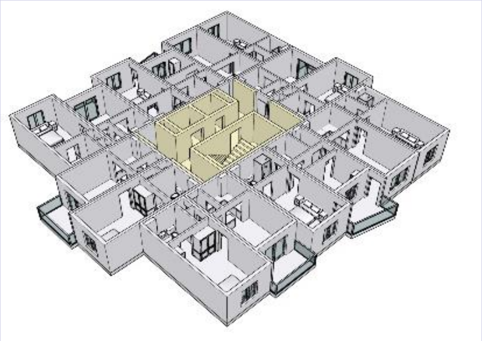
- Building construction is highly developed and regulated in Hong Kong requiring tremendous technical and managerial skills as well as financial management.

- Building construction using conventional reinforced concrete construction, after 30 years of practice and development, is still ***NOT*** seamless here in Hong Kong !

- Innovative structural engineering design is needed to develop new structural systems for MiC highrise buildings using high performance materials to delivery buildings of same quality.







# Hong Kong Modular Integrated Construction (MiC) Innovations

## ITF Project by NAMI and CNERC-Steel

**Challenges to adopt MiC in Hong Kong**

- Optimal solutions for competing requirements are difficult to be achieved in design, approval, costing, and construction.
- Suppliers of modular units find it very difficult to enter the market in Hong Kong.

- Technical barriers are challenging:

Architectural Design *for maximizing GFA*

- restrictive layouts to serve various building use.
- reduced usable floor areas because of the presence of double walls.

Structural Engineering Design *for achieving high structural integrity*

- many small sized columns and walls to resist gravity and wind loads.
- presence of many construction joints within building systems.

# Hong Kong Modular Integrated Construction (MiC) Innovations

## ITF Project by NAMI and CNERC-Steel

**Innovation for MiC Highrise Buildings**

- Materials and engineering research into high performance constructional materials for high-rise MiC buildings
- Advanced structural engineering innovation for residential buildings:
  - i) 3 ~ 6 storeys
  - ii) 8 ~ 20 storeys
  - iii) up to 40 storeys

Technical considerations:

Self-weights of modular units / reduced member sizes and increased usable floor areas / load resisting systems / construction joints / fire resistance / durability

Outcomes:

Effective use of materials / structural framing for highrise buildings / effective joints / construction methods and procedures / technical guides / examples and case studies

# Hong Kong Modular Integrated Construction (MiC) Innovations

## ITF Project by NAMI and CNERC-Steel

In this project, the research work should be conducted in the following phases:

- Phase A *Preliminary Studies*
- Phase B1 *High performance materials*
  B2 *Innovative Structural Engineering Design*
- Phase C *Compilation of Design Guidance*

Design and construction of all MiC buildings in Hong Kong should comply with the local building control regulations.

It should be noted that:

a) Hong Kong has one of the highest requirements on resistances against wind loads in the world.
b) Hong Kong requires fire safety in modular units to be in the same standard of conventional buildings.

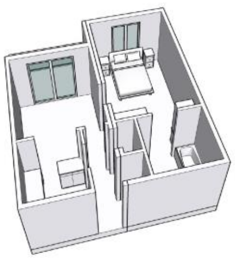
## Phase A: Preliminary studies

Layout design:

Building layout plans should be designed to enable effective modularization on repetitive units while maximizing useable floor areas.

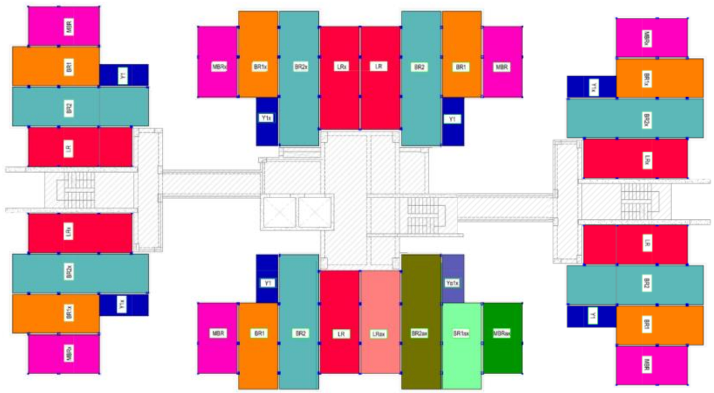
Layout plans for the following typical building types will be identified for subsequent development:

a) student halls of residence, youth hostels, and hotels
b) public residential buildings
c) private residential and commercial buildings



Two coordinated concrete modular units

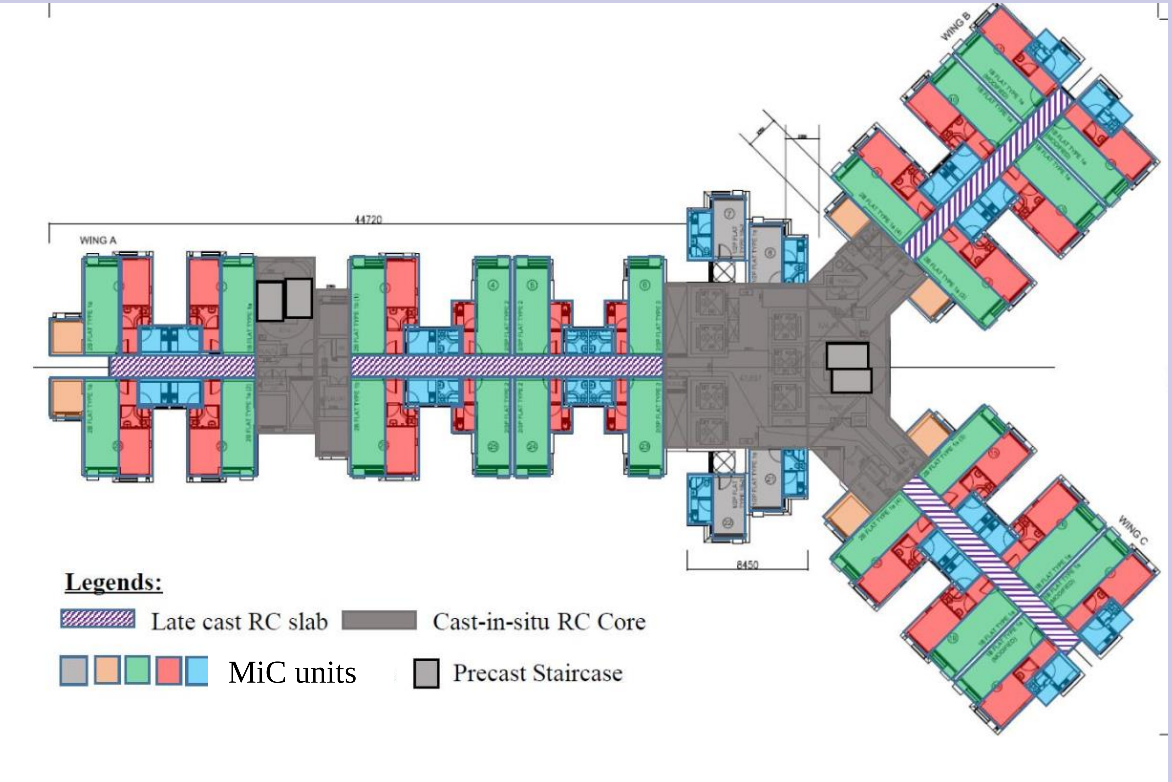
A steel modular unit



Modularization on architectural layout plan to identify repetitive units

## Phase A: Preliminary studies

Layout design:



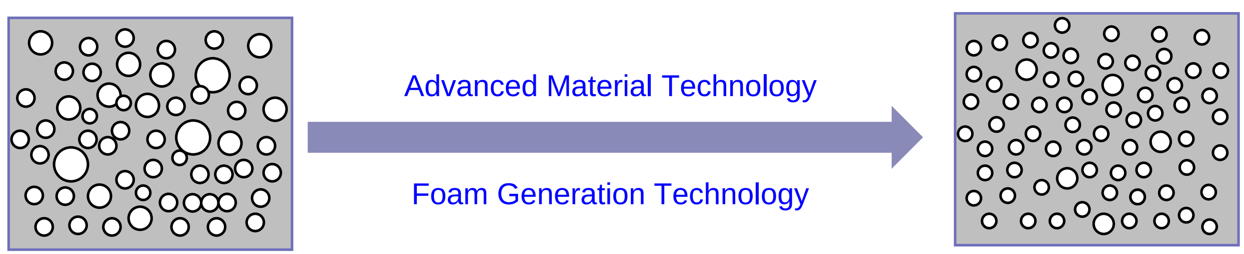

Modularization of a typical plan of a student hostel

## Phase B1 High performance materials

### High Strength Foam Concrete for Floor Slab

- **Target: 30 MPa @ 1200 ~ 1400 kg/m$^3$**
- Present status: 15 ~ 25 MPa @ 1200 ~ 1400 kg/m$^3$
  - Large air voids (> 0.1 mm) and wide size distribution due to air bubble coalescence.
  - Air bubble coalescence becomes more significant when the introduced air content exceeds 40% (equivalent to density of about 1300 ~ 1400 kg/m$^3$ )

***Making <u>high strength foam concrete</u> by <u>reducing the air void size</u>, i.e. below 0.1mm, and <u>narrowing down the size distribution of air voids</u>***




Conventional cellular concrete

Cellular concrete to be developed

## Phase B1 High performance materials

### High Strength Concrete for Wall

- **Target: C80 concrete with at least 1 hour fire resistance period (with limited spalling), and enhanced resistance to water and chloride ion penetration.**
  - Providing fire and corrosion protection to steel components
- Technical approach for developing concrete mix design
  - High binder content and low water/binder ratio
  - Usage of silica fume and/or nanoparticles
  - Optimized particle packing
  - Introduction of polymeric and/or steel fiber

**Dense structure provide high strength and low permeability**

**Fiber providing vapor evaporation path and bridging to reduce spalling**

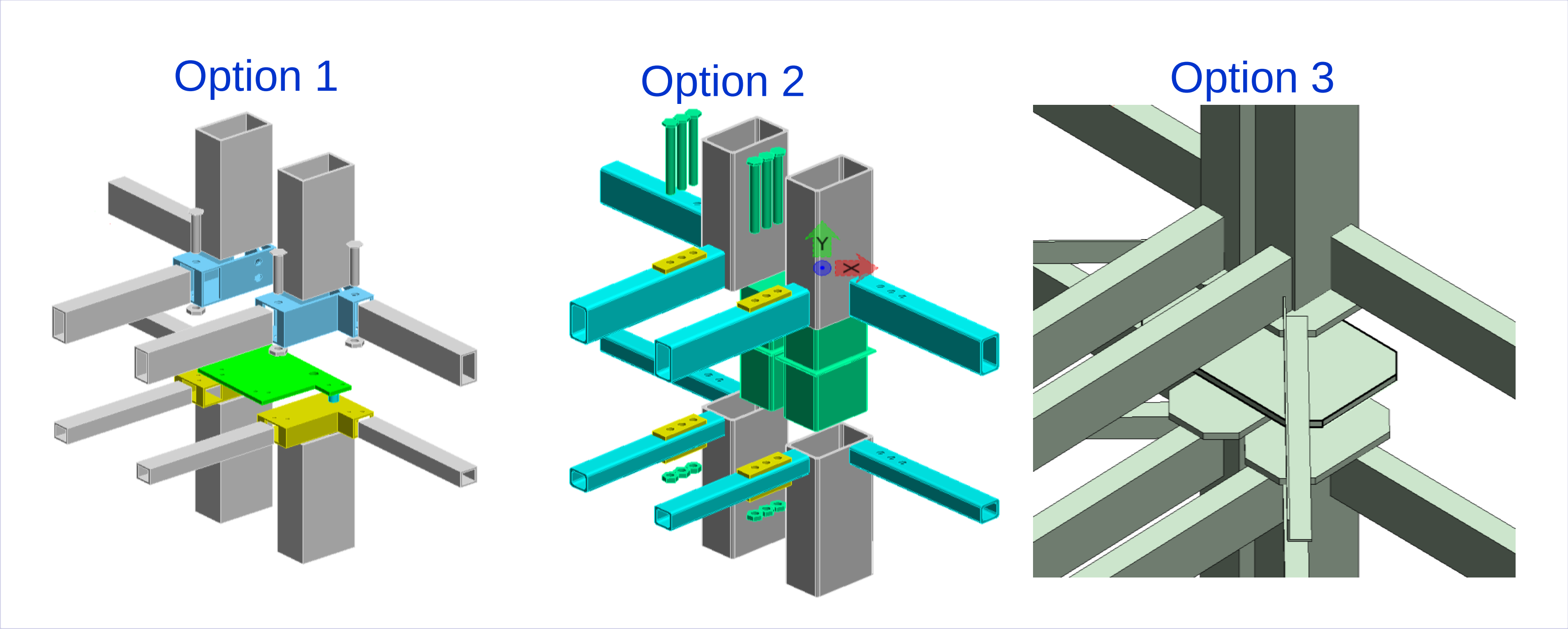
Setups for strength, permeability and fire resistance measurements

# Phase B2 Innovative Structural Engineering Design

Design issues

Connections between modular units

Case 1: Joints of two corner connections – Upper units and Lower units



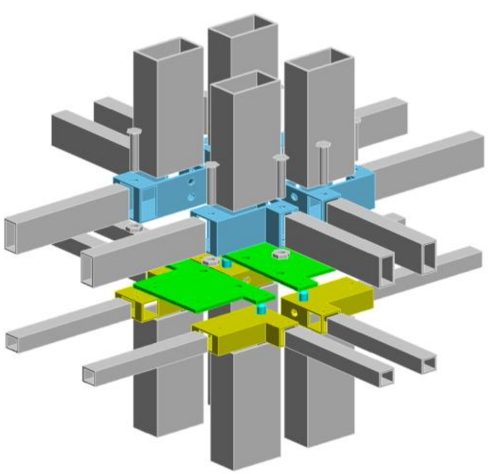
## Phase B2   Innovative Structural Engineering Design`

Design issues

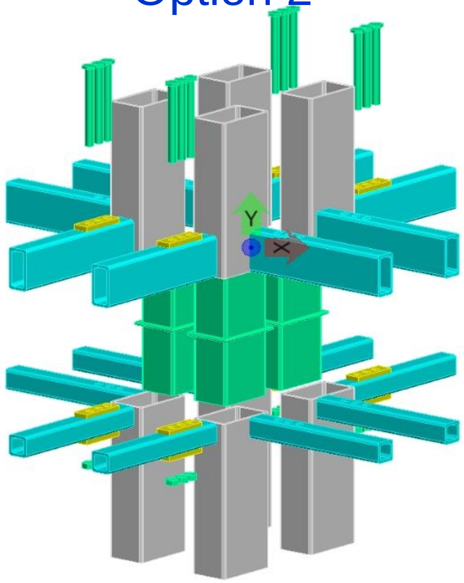
Connections between modular units

Case 2: Joints of four corner connections – Upper units and Lower units

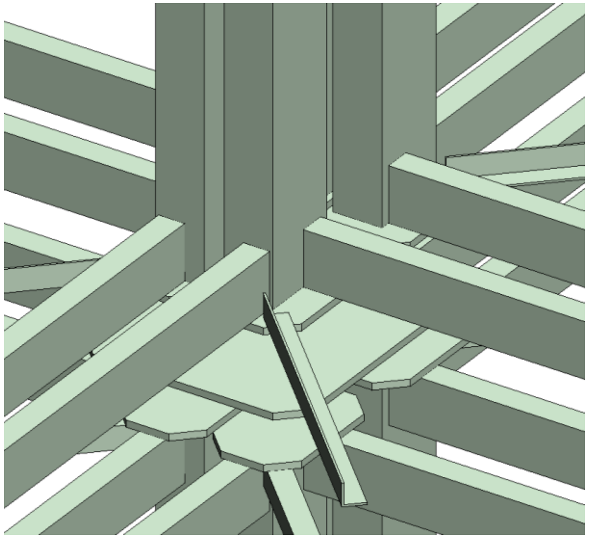
Option 1



Option 2




Option 3



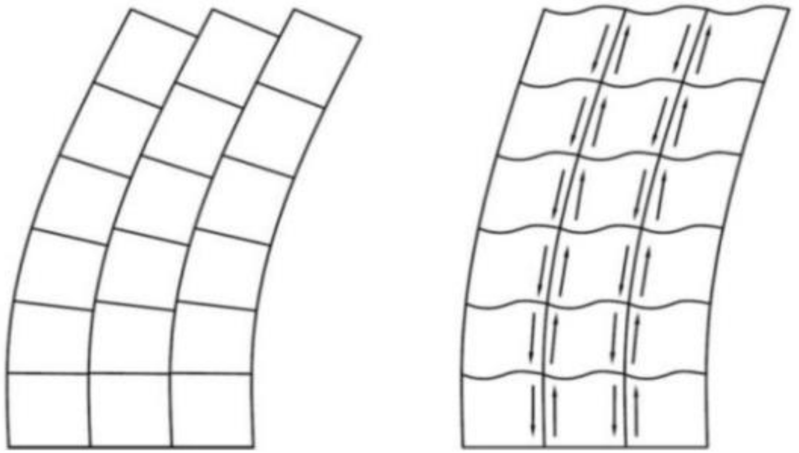
## Phase B2 Innovative Structural Engineering Design

Design issues

Continuity across adjacent modular units

Owing to the use of modular units, there is little structural continuity across adjacent modular units, and hence, these units tend to behave separately under lateral loads.

In order to improve structural efficiency, coupling between adjacent modular units should be provided at joints, and construction methods should be improved to ascertain a high degree of coupling in practice assumed in the structural design.



a) No vertical shear transfer

b) Effective vertical shear transfer through coupling at joints

Vertical shear transfer between adjacent modular units

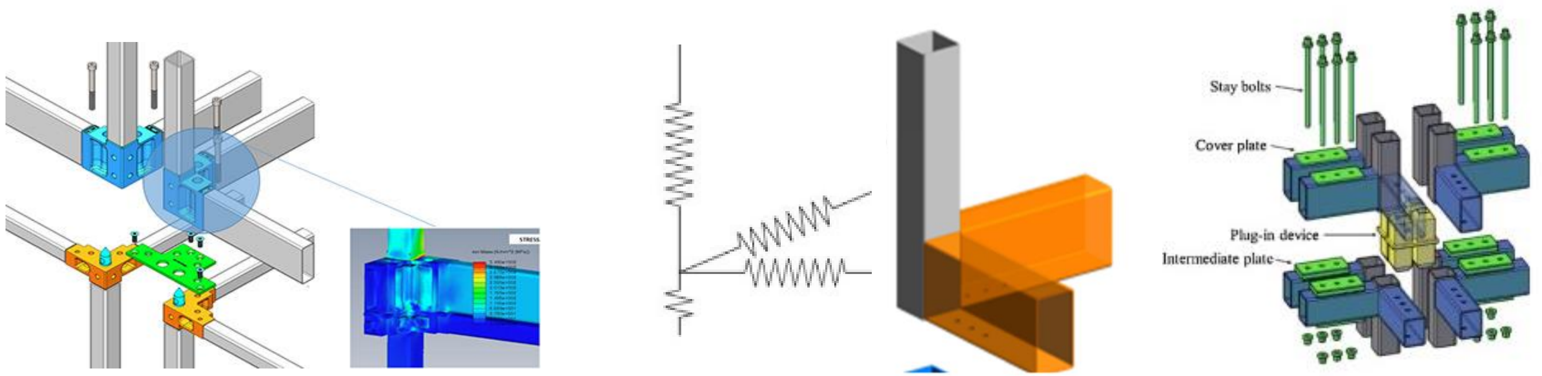
*Effective horizontal force resisting systems*

## Phase B2 Innovative Structural Engineering Design

Design issues

Connections between modular units

It is essential to develop accurate prediction models to determine strength and stiffness of various practical connections commonly used in MiC. Improvements to the connections should also be made with enhanced strength and stiffness.




a) Practical connections between modular units

b) Joints with different translational and rotational springs to allow for different degrees of continuity

c) Alternative connections between modular units

Prediction models to determine strength and stiffness of MiC connections

## Phase B2 Innovative Structural Engineering Design`

Computer modelling:

New modelling techniques in simulating the following should be developed:

- Change in loads, load paths and structural forms during stacking
- Modular units with different structural forms and different combinations of high performance materials having different strengths and stiffnesses
- Connections and joints in building systems with partial continuity against both global and local actions

## Phase C – Compilation of Technical Guides

A number of technical guides will be prepared to present:

- Effective use of high performance materials
- Innovative structural forms and connections
- Fire resistances and durability
- Construction methods and procedures
- Typical modular units and technical specifications

To provide a definitive Technical Guide on architectural and engineering design (including architectural, structural, fire, acoustic, building services considerations), demonstrating MiC technology in youth and student hostels, young families and transitional social housing, etc.

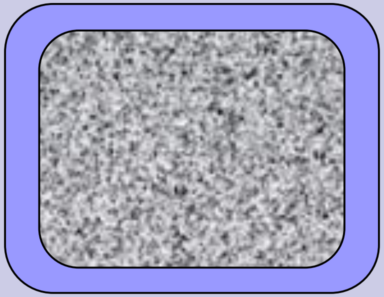
Deliverables

- Provision of the first Technical Guide to inform construction professionals
- Compilation of examples to demonstrate MiC technology and its multi-benefits
- Consolidation of requirements on architectural and engineering design

# High Performance Materials for MiC High-rise Buildings

High performance materials for effective design in
i) highrise buildings of 30 ~ 60 storeys, or
ii) building systems with heavily loaded columns

EN1994-1: Eurocode 4 covers:
i) *S235 ~ S460* steel, and
ii) *C25 ~ C60* concrete



*No reinforcements*

To extend codified design rules to cover:
high strength steel **S460, S690 and S960**
high strength concrete **C100 ~ C150**

Physical tests: cold-formed rectangular hollow sections:
***250 x 150 x 16*** ***150 x 100 x 10***
Stocky columns / slender columns / weld fracture connections
System tests on multiple MiC units to confirm partial continuity of connections

Design rules:
Section classification, axial buckling, combined compression and bending

Challenge:
Tremendous loading requirements, hence, very difficult to be carried out,
Quality control on high strength steel and concrete

# Progressive Collapse / Disproportionate Collapse
## Structural integrity / robustness against accidental loads

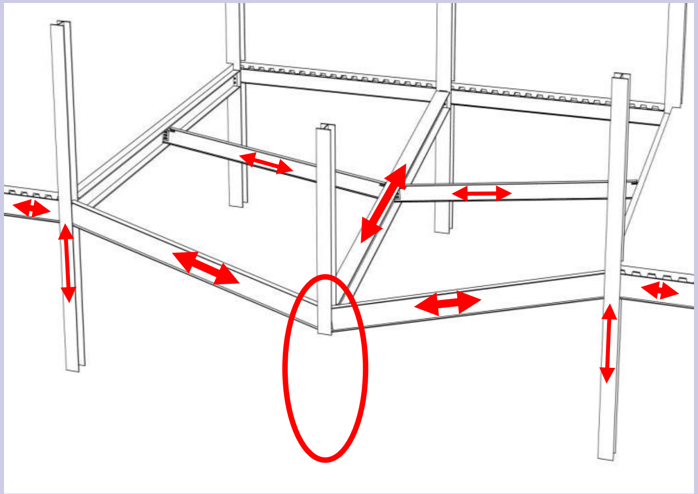
*Ronan Point Collapse in North London in 1967.*

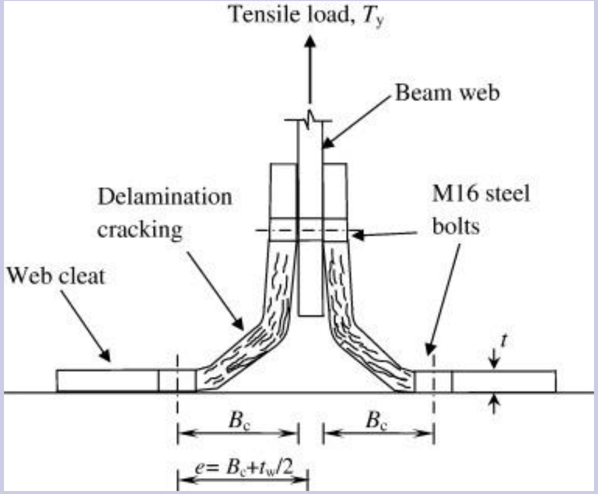
This collapse was triggered by a gas leak on the 18th floor of the tower block. The building system comprised mutually supporting precast concrete panels, and the blast blew out a wall panel, causing a collapse of the floors above and below.

## Progressive Collapse / Disproportionate Collapse
### Structural integrity / robustness against accidental loads

- All happen quickly ➡ dynamic effects
  - inelastic and gross deformations
  - responses in members and connections under complex loadings
- An ability to attain a *new* equilibrium position determines whether such a progressive collapse will occur or not.
- Prevent separation of members / components ➡ robustness

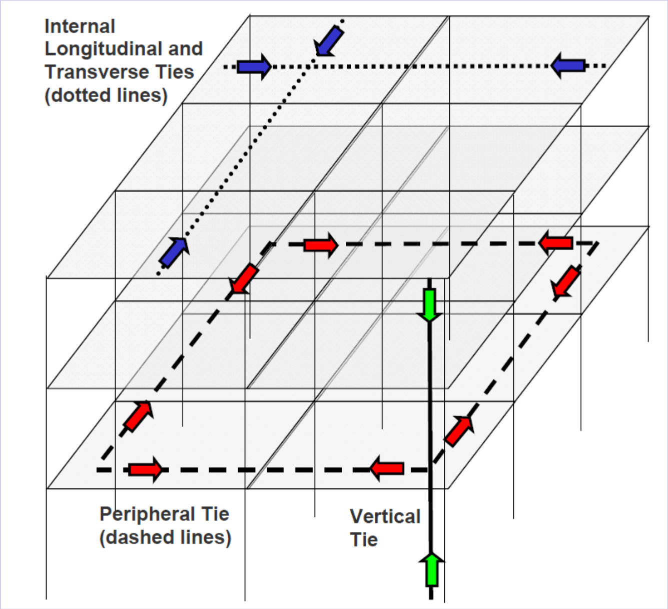
*integrity of beam to column connections is essential*

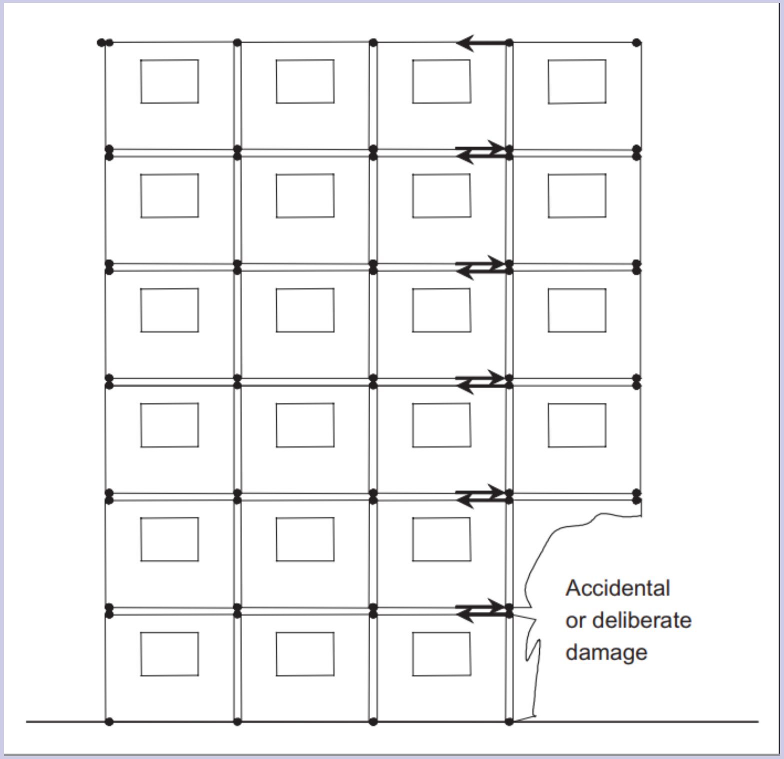




# Progressive Collapse / Disproportionate Collapse
## Structural integrity / robustness against accidental loads

- To design and provide tensile resistances in beam to column connections
- To identify load paths for these ties, and provide a considered approach to the overall arrangements.





Reference:
Lawson, P. M., Byfield, M. P., Popo-Ola, S. O., & Grubb, P. J. (2008). Robustness of light steel frames and modular construction. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 161(1), 3-16.

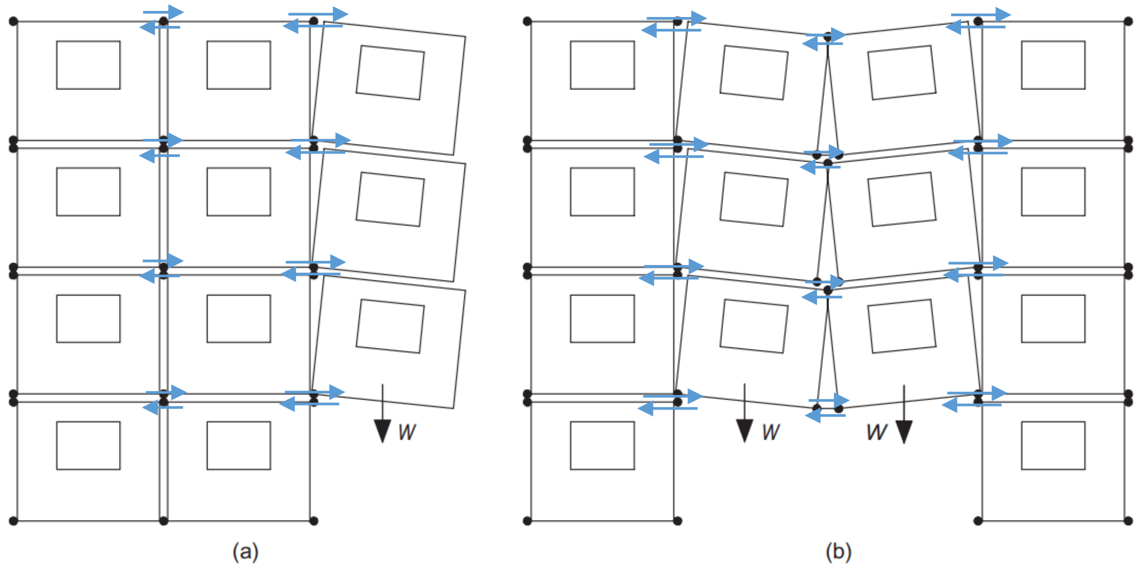



Fig. 16. Robustness scenarios in modular construction

10 Structures & Buildings 161 Issue SB1 Robustness of light steel frames and modular construction Lawson et al.

The alternative load path route is advocated as the most appropriate means by which light steel modular construction can comply with the Building Regulations concerning robustness.

Reference:
Lawson, P. M., Byfield, M. P., Popo-Ola, S. O., & Grubb, P. J. (2008). Robustness of light steel frames and modular construction. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 161(1), 3-16.

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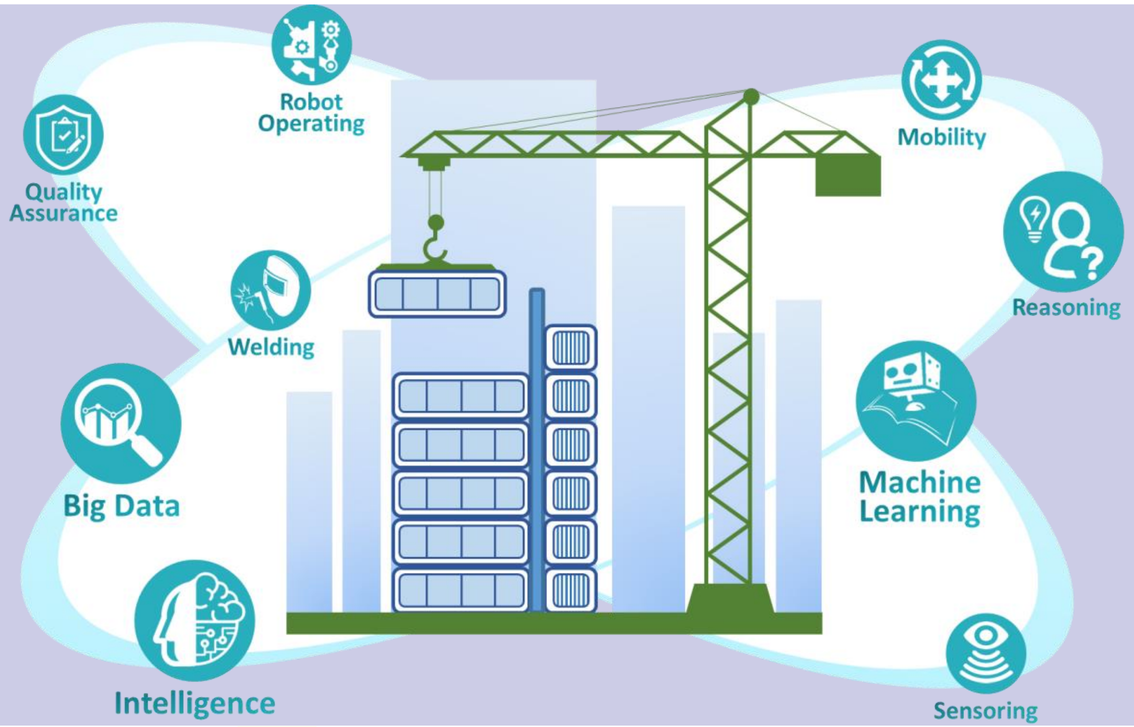
# Laboratory on Modular Integrated Construction

## *with Artificial Intelligence and Robotic Technology*

THE UNIVERSITY OF MELBOURNE

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**Application to InnoHK – Global Research Collaboration**

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# Laboratory on Modular Integrated Construction

*with Artificial Intelligence and Robotic Technology*

## Mission

To provide

- integrated and optimized architectural and engineering design, coordinated fabrication, delivery and site erection for MiC buildings, and their sensing on built environments and monitoring on structural behaviour under environmental effects and loadings

- development and application of artificial intelligence and robotic technology to create new tools to enhance design, construction and monitoring processes of MiC buildings

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# Laboratory on Modular Integrated Construction

*with Artificial Intelligence and Robotic Technology*

The proposed Laboratory will greatly facilitate development and applications of AIR technology in MiC:

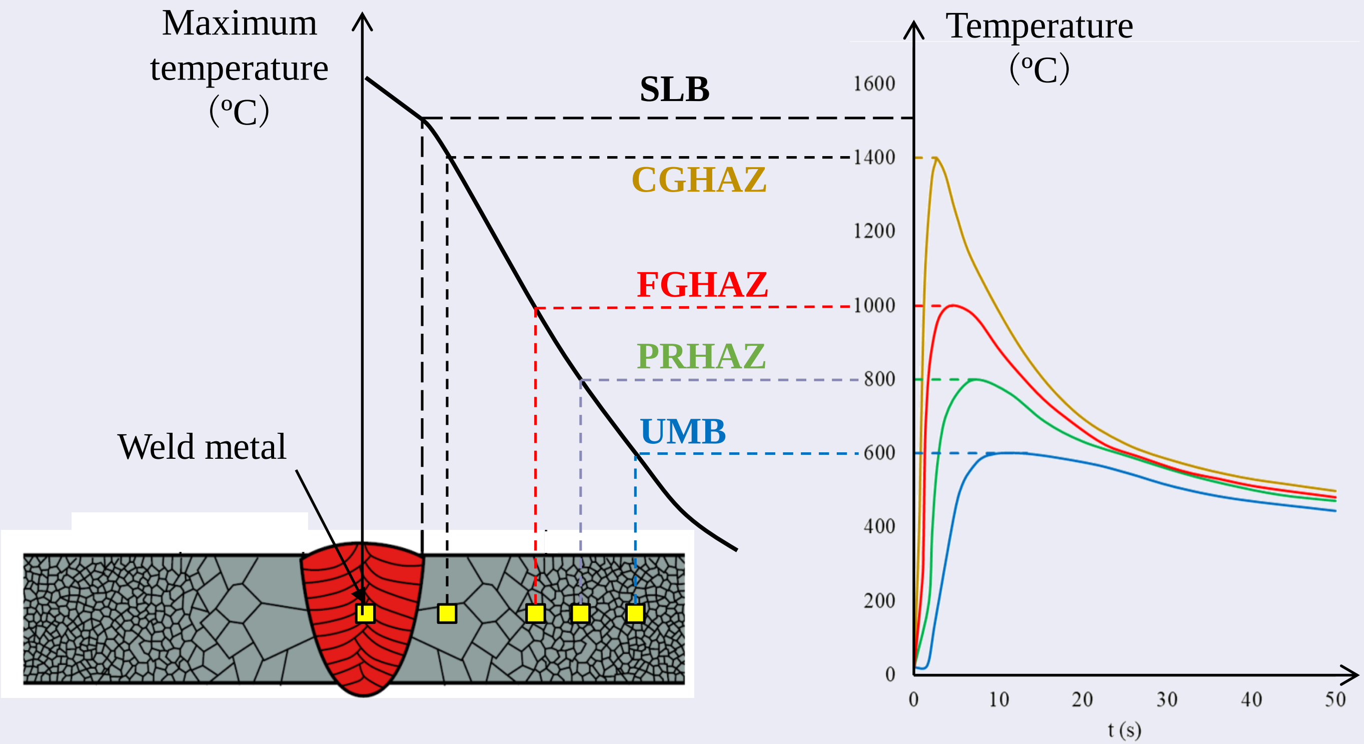
- Artificial intelligence based knowledge platforms for both architectural and engineering design of MiC buildings.
- Smart structural systems and connections of MiC buildings with fully digitalized construction processes using a Building Information Modelling platform.
- Effective steel and steel-concrete hybrid systems of MiC buildings for optimized functionality, safety, constructability and durability.

# Investigation into structural behaviour of high strength S690 steels and their welded sections

- Mechanical properties of S690 steels
- Residual stresses of S690 welded H- and I-sections
- Stocky columns of welded S690 H-sections
- Slender columns of welded S690 H-sections
- Steel beams of welded S690 I-sections
- Strength reduction and softening in S690 welded joints
- Effects of welding onto microstructures of S690 welded joints
- Stocky columns of S690 welded H-sections with splices (butt-welded joints)

# Strength reduction and softening in S690 welded joints

## Metallurgical zones at different temperatures




**SLB**: solid-liquid boundary

**CGHAZ**: coarse grain heat affected zone

**FGHAZ**: fine grain heat affected zone

**PRHAZ**: partially recyclized heat affected zone

**UMB**: unaffected base material

# Robotic welding for Q690 steel sections

Robotic welder for GMAW

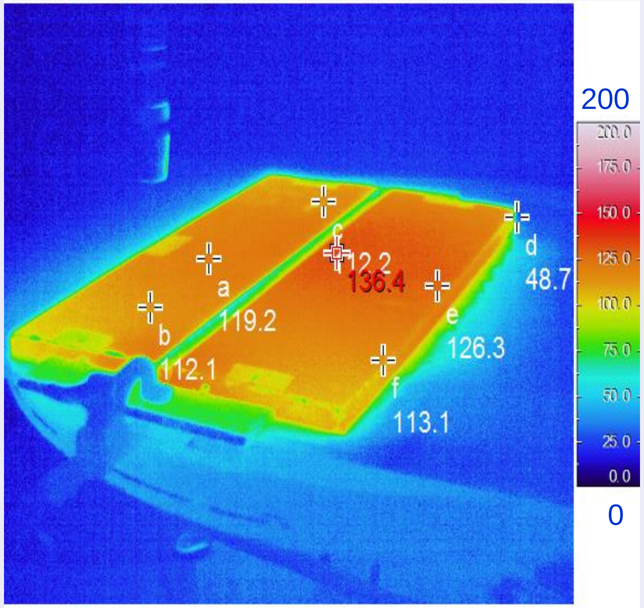
a) Infrared camera to record temperature history during welding

b) Infrared thermometer to monitor temperature

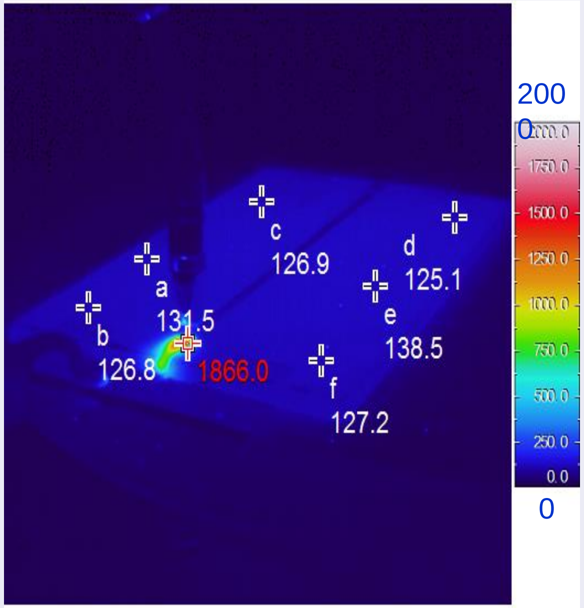
Electric blanket for pre-heating and post-heating

# Robotic welding for Q690 steel sections

Well-prepared specimen



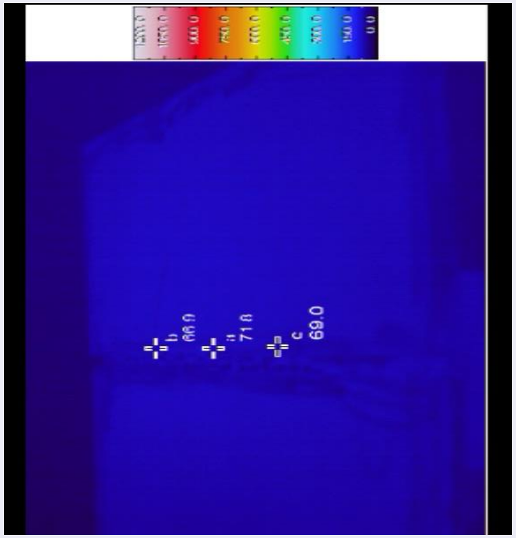

Measured temperature field during pre-heating




Measured temperature field during welding

## Robotic welding and monitoring

# Robotic welding and monitoring



Surface temperatures and thermal images

Robotic welding system

Molten weld metal

# Visual inspection during welding

Lack of fusion ahead of arc due to low current

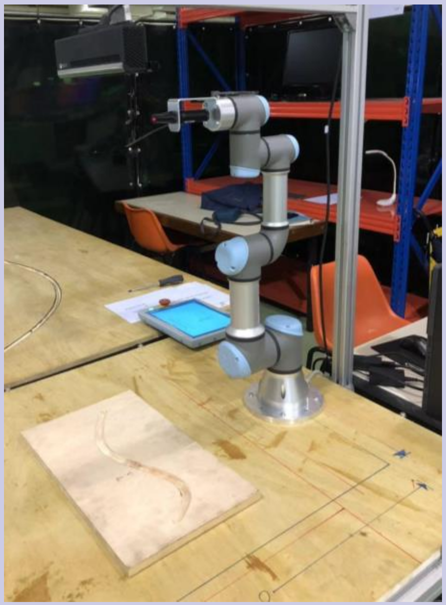
Decrease in weld size as weld pool burns through

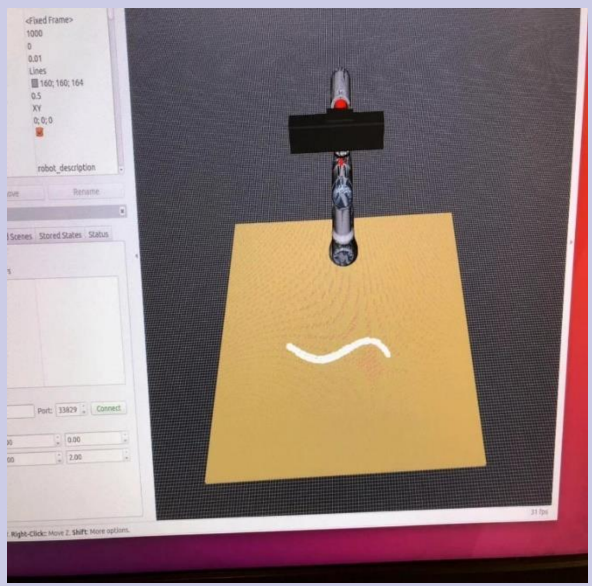
Torch misaligned to fillet joint

Porosity due to lack of shielding gas

# Robotic welding technology

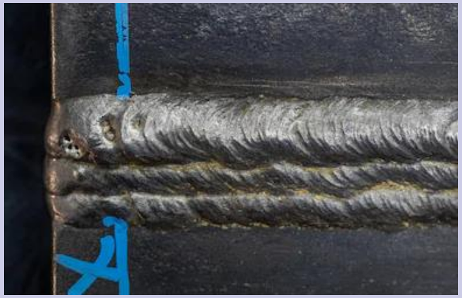
Auto tracking and trajectory planning






# AI Visual Inspection of Welding Defects after Welding

- Image processing, pattern recognition
- Neural Network, Deep Learning and Classifications
- Third party (independent) AI assisted inspection and recording



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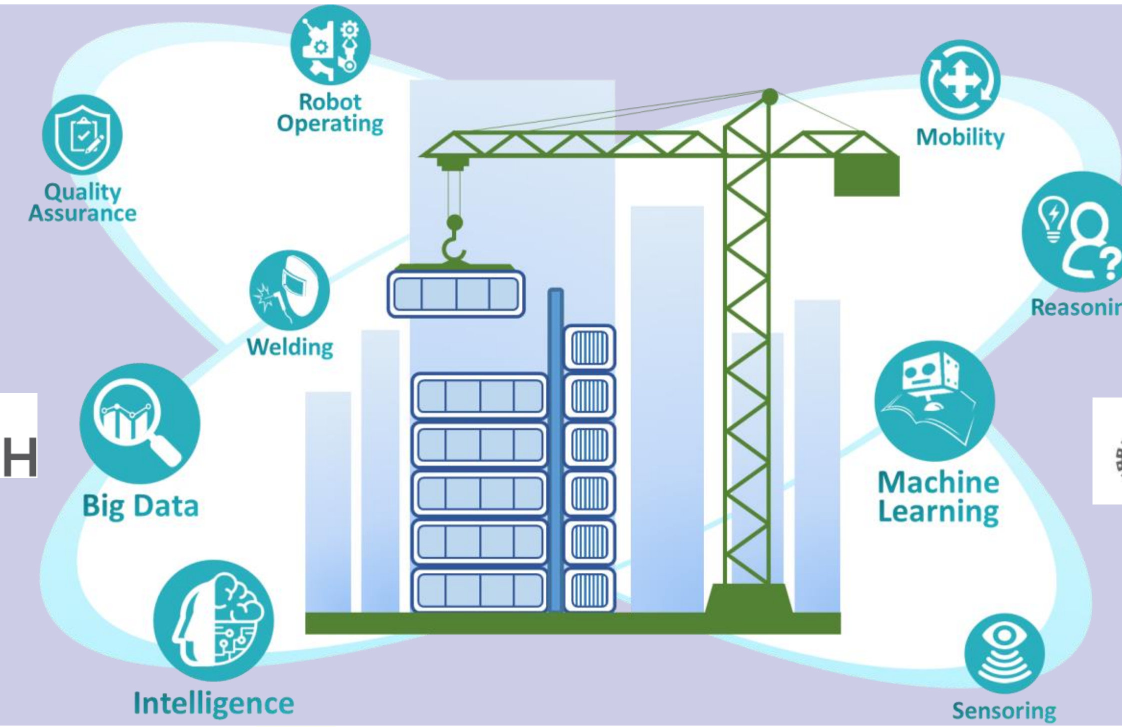


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