Title: **Assessment of the Life Safety Aspects and Structural Robustness of High Rise Buildings in Hong Kong**

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ASSESSMENT OF THE LIFE SAFETY ASPECTS AND STRUCTURAL ROBUSTNESS OF HIGH RISE BUILDINGS IN HONG KONG

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Abstract

At the time of the events in New York of September 11, 2001, a 420m high 88 storey office building in Hong Kong was constructed up to the 20th floor level. This paper describes some of the investigations which were undertaken immediately following the attacks to assess overall robustness of the building and other life safety related issues. The paper presents the findings of studies that were undertaken on the resistance of key elements under the effects of impact loading and intense fire scenarios. An important finding from the studies was the importance of **dynamic** robustness considerations and the beneficial effects of inherent structural ductility and energy absorption in arresting disproportionate collapse.

Keywords: Tall buildings, Performance-based, Life-safety, Structural integrity, Dynamic, Robustness

1. Introduction

At the time of the events in New York on September 11, 2001, Two International Finance Centre (Two IFC) was under construction in Hong Kong. The building, now largely complete, is an 88 storey, 420m landmark structure providing premium grade A office accommodation in the Central Business District The events in New York resulted in an immediate review of the design of Two IFC. The key questions were:-

- How robust is the present design?
- How would the building, or key elements of the building, perform under various impact scenarios?
- How resilient is the fire resistance of the structure?
- What are the escape provisions within the building, and how do these compare with those which in other parts of the World?

It should be noted that, as a result of the immediate demands of the on-going construction of Two IFC, the studies undertaken to address the above were conducted at an early stage in the aftermath of 9/11. Consequently, they were carried out prior to much of the post-9/11 forensic and research information being available. The studies have, however, provided feedback at an early stage, to some of the subsequent definitive recommendations as to 'the way forward' in terms of the design of tall buildings (Institution of Structural Engineers, 2002).

Whilst the findings reported herein suggest that certain tall buildings in Hong Kong demonstrate enhanced robustness and egress provisions compared to other similar buildings around the world, there is no suggestion that these buildings would be necessarily be able to resist the type of extreme event experienced by the World Trade Center towers in New York.

2. The Two International Finance Centre

Two IFC forms part of Hong Kong Station Development on the Central Reclamation Hong Kong. Developers of the site are IFC Development Limited - a joint venture between Sun Hung Kai Properties Ltd, Henderson Land Development Co Ltd, Bank of China Group Investment Ltd, the Hong Kong & China Gas Co Ltd. The site is being developed in partnership with the land owner, the Mass Transit Railway Corporation (MTRC). The design, construction and leasing process is managed by Central Waterfront Property Project Management Co Ltd (CWP), which is jointly owned by Sun Hung Kai Properties Ltd and Henderson Land Development Co Ltd. Architects for the project are Cesar Pelli & Associates and Rocco Design Limited with Ove Arup & Partners Hong Kong (Arup) providing structural and geotechnical engineering consultancy services.

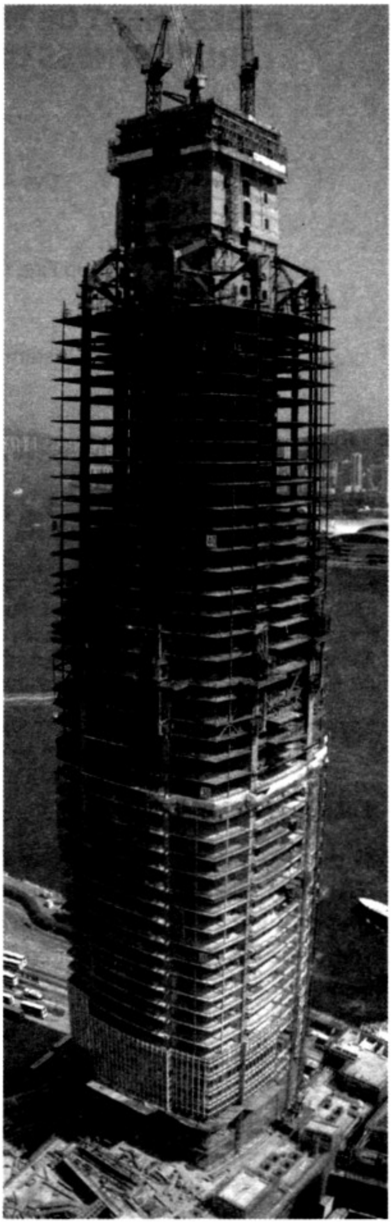

Fig.1 Partially Constructed Two IFC Tower

In the context of the studies that were undertaken, the following aspects of the tower are significant:-

- The tower comprises a reinforced concrete core (27m x 29m at the base).
- The core is stabilised by three levels of triple storey steel truss outriggers. These are located in the mechanical and refuge floors.
- The fundamental requirement for flexible office layouts, and the desire to maximise the panoramic views, necessitated that the perimeter structure should be kept to a minimum. This led to a stability solution employing eight main megacolumns (two per face). The columns are at 24m centres on the four faces of the towers and mobilised directly by the outrigger.
- The megacolumns are of concrete encased composite construction. The floors of the tower are similarly of composite construction (concrete slab on steel decking supported by steel beams).
- The tower was designed and constructed to comply with Hong Kong codes which, in terms of structural requirements, comply largely with the requirements of British Standards.
- The escape provisions in the tower (staircases and refuge floor requirements) complied with the requirements of the Hong Kong Means of Escape regulations (Hong Kong Buildings Department, 1996).

Fig. 1 shows the status of the building construction highlighting the structural form at the perimeter. A paper describing the design and construction of the tower is available. (Gibbons et al, 2002).

3. Structural Considerations

The following studies were undertaken to assess the structural implications:-

- Analytical assessment of the impact of aircraft components on the key elements of the structure.

- Consideration of the 'vapourisation' of key elements of the structure - i.e. instantaneous removal of key vertical elements, without consideration as to the extreme event which could result in their removal.
- Consideration of the dynamic effects of falling floor debris and the requirements for the energy absorption characteristics of the floor.

3.1 Impact studies on Key Elements

In any Tall Building, the robustness of the vertical elements of the structure is a key consideration. This was particularly important in the case of Two IFC given that the perimeter frame comprised of only eight main columns. Analytical studies undertaken by the Arup Extreme Events Mitigation Task Force investigated the performance of a range of typical columns in high rise structures when subjected to the impact from an aircraft engine traveling at speed. It was considered that an aircraft engine, along with items such as landing gear, represent the most dense parts of the aircraft and hence have the potential to inflict the most damage on structural elements. The studies where undertaken using LS-Dyna finite element software which allows a full consideration of non-linear geometric deformations and dynamic and non-linear material properties.

It should be noted that these studies were not intended to re-create the scenario of 9/11. They were performed, assuming lower simulated impact velocities more representative of accidental events, to investigate the relative performance of a number of structural forms. The key parameters in the investigation were as follows (Fig. 2):-

- Engine speed – 200mph (89.4m/s)
- Engine model – finite element model comprising 5mm thick outer and 10mm inner aluminum casing for the engine housing. Central turbine shaft comprising a 0.6m solid aluminum cylinder.
- Mega columns studied – 3m x 1.8m reinforced concrete encased composite column housing two 604kg/m steel sections.

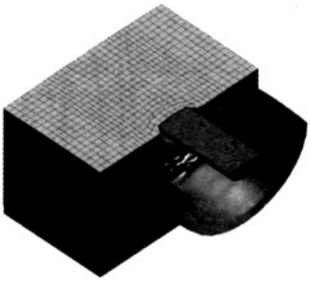

Fig. 2 - Cutaway of Engine Impact with Megacolumn

The key findings of these studies were that, the composite megacolumns of the Two IFC performed well – exhibiting only limited concrete crushing and plastic straining of the steel sections. This compares with studies undertaken on steel only sections used on 'gravity only' perimeter frames with smaller and more frequent columns. Specifically, studies on a 551kg/m steel section predicted that the shaft of the engine would pierce through the columns with an exit velocity more than 50% of the impact velocity.

The megacolumns in Two IFC are substantial concrete encased steel composite sections. This provides an economical solution in Hong Kong, capitalizing on the relative low cost of reinforced concrete whilst addressing the need to provide columns of high strength and stiffness to address high design typhoon wind loads. The substantial concrete encasement provided energy absorption and acted as protection to the significant steel core within the section. Based on the these initial studies, it provided re-assurances on the relative robustness of this type of key element.

Similar studies were undertaken on the robustness and integrity of concrete cores when subjected to impact. It should be noted that this form of core construction for tall buildings is prolific in Hong Kong due to cost considerations.

The studies showed under similar impact scenarios as those described above, 300mm thick core walls offered a high degree of residual strength despite being unable to arrest the passage of the dense components of the aircraft engine (eg. central engine shaft).

3.2 Vapourisation of Key Elements

One of the key issues facing the designers of buildings is the nature of the extreme event to be considered. As described above, whilst the columns of Two IFC tower appear to perform well under modest impact scenarios, designing columns (or other elements) for the most demanding scenarios is considered impractical. It is not inconceivable (indeed it is highly probable) that bigger, faster aircraft will be developed over the design life of the building with the potential to impair greater damage than that which can presently be envisaged. Similarly, other destructive means may be developed which exceed our present understanding and which could compromise the integrity of such robust elements.

Rather than ponder too long on what these present, or future, scenarios might be (because, invariably they could be exceeded) it is important that the goal of sound structural design is not lost. Specifically, that a sensible tall building structural solution results which is not unduly sensitive to the removal of key elements of the structure. In the event that such elements are removed (irrespective of what may cause the removal) it is important that such buildings do not exhibit damage (collapse) which is disproportionate to the cause.

The studies on Two IFC therefore considered a 'what-if' scenario. What-if, two of the eight megacolumns were removed at ground level. The megacolumns at ground level are substantial (2.3m x 3.5m) concrete encased elements comprising a multiple steel core utilizing 90mm thick steel sections. It is inconceivable to think what event could manifest their removal, nevertheless, the studies examined the implications. Specifically - second-order analyses global analyses of the performance of the tower were undertaken with two adjacent corner megacolumns removed (Fig. 3).

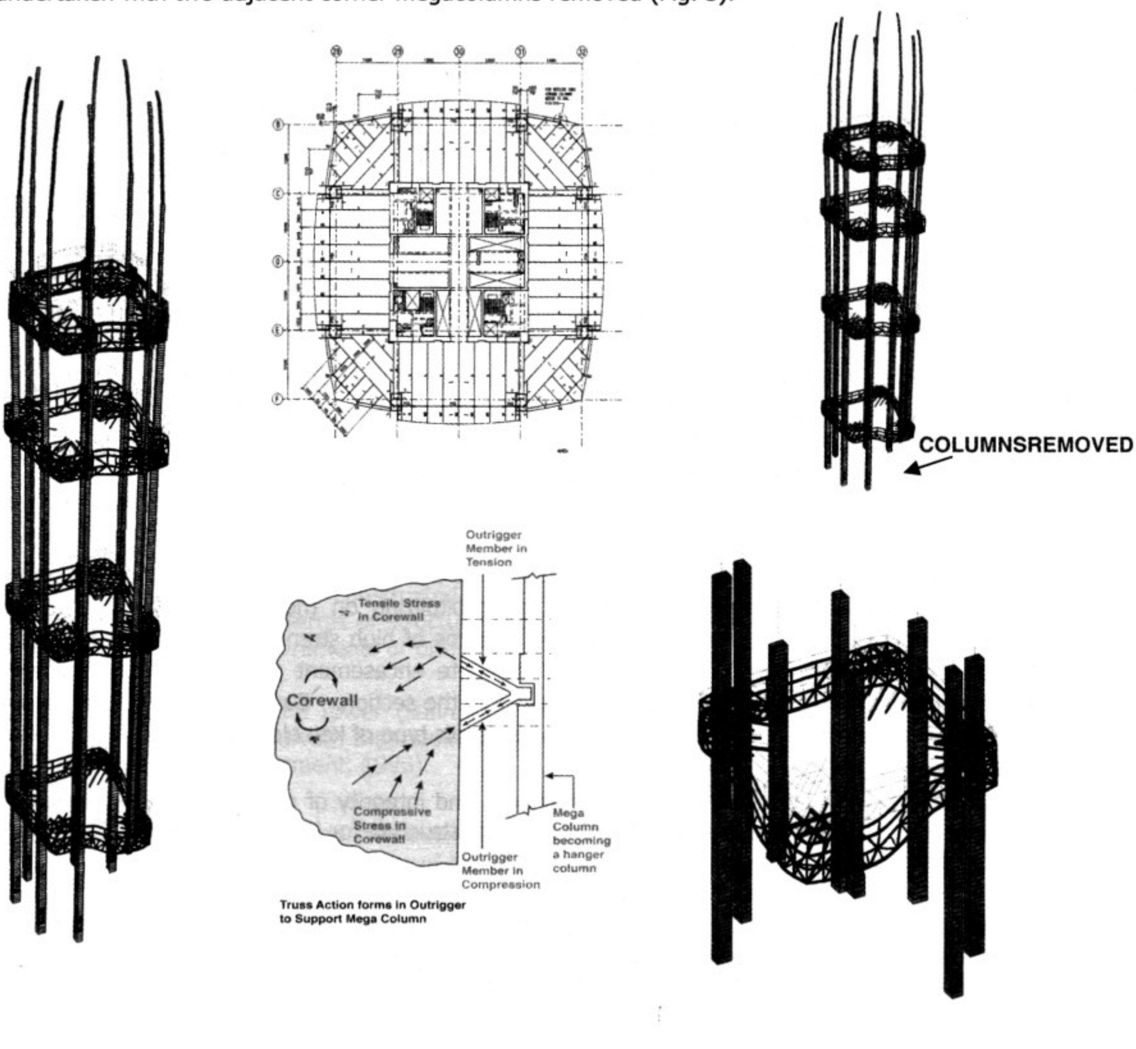

Fig. 3 Removal of two Megacolumns Columns (exaggerated deformation)

The key findings were as follows:-

- The tower remained stable despite the columns being removed.
- The tower experienced a gravity load path re-distribution.
- This involved mobilization of the outriggers as 'vertical load props' to compensate for the removal of the key components from the perimeter frame. It should be noted that the outriggers are designed under normal conditions to resist wind load only.
- The increased gravity load in the outriggers is resisted by the reinforced concrete core which was demonstrated to adequately redistribute these gravity loads,

The key reason for the tower to be able to survive in such a damaged state is the need to design the building under normal conditions to resist large one-in-fifty year (64m/s design speed) typhoon winds. Clearly, this design scenario has not been considered in combination with the tower in a damaged state. Typically, in Hong Kong, and recognizing the large design wind loads, all vertical structure tends to be mobilized in providing lateral stability to minimize overall structural costs. As a consequence, and as was in evidence from these studies, vertical elements have a significant residual capacity in the absence of wind to permit resistance of re-distributed gravity load in an extreme event.

3.3 Effect of collapse of the floors

In the early stages following the events of 9/11, it was evident that many questions were raised with regard to the effect of the loss of restraint to the perimeter columns due to the removal of the supported floor diaphragms. This combined with the effects of fire is seen as a key factor associated with the softening of the perimeter columns and the removal of their residual capacity.

One of the studies undertaken on Two IFC was to examine the extent of removal of column restraint (ie. removal of floors) which could be tolerated before the columns were unable to resist the applied load due to bucking considerations. This study was conducted in the absence of fire effects (the integrity of the concrete encased megacolumns considered to be high in the presence of fire) and also in the absence of any significant damage to the column (mindful of the impact studies reported above).

The findings demonstrated that columns could continue to support the applied load if floor diaphragm restraint was removed over typically 15 storeys, reducing to 10 storeys towards the top of the building (Fig. 4).

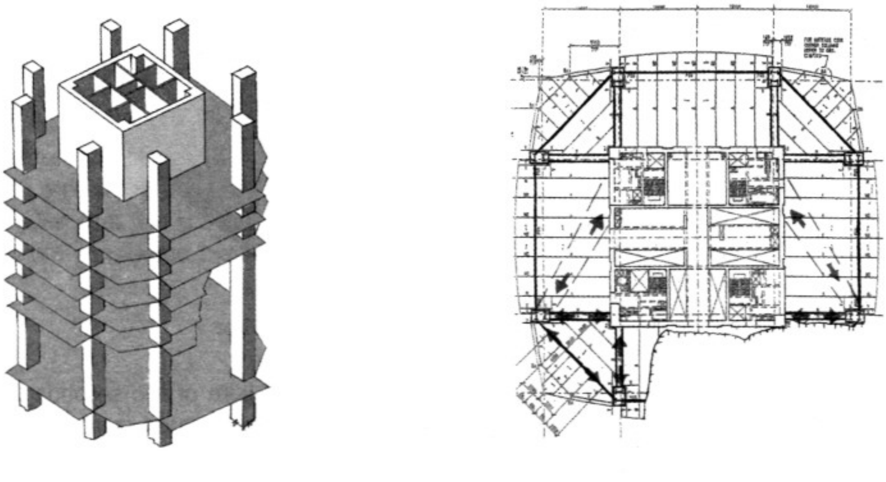

Fig. 4 Removal of Floor Diaphragms and Column Restraint

This would appear to demonstrate the enhanced resistance of megacolumn type structures in the event that there is an extreme event which results in the removal of floor plate diaphragms, and in which the frequency of restraint of the perimeter columns is compromised. It is evident that the increased capacity of the megacolumns on Two IFC (due to their being only two per face, the high Hong Kong wind loads, and the increased buckling restraint due to concrete encasement) results in a large unrestrained length being tolerable.

In considering extreme events, be they blast or impact, it is likely that debris (typically from the floors) will result. It is important that such debris can be 'arrested' by the floor below (typically operating at normal temperatures) such that a progressive collapse does not develop through the structure (domino fashion), thereby preventing a collapse which is disproportionate to the cause. Similarly, in the event that a floor is damaged (but without significant debris), it is conceivable that premature collapse of the floor may result under any subsequent fire. Again, it is imperative that the collapse of such a damaged floor can be arrested by the 'cold floors' below.

Arup undertook studies of the behavior of floor plates of the Two IFC under normal 'non-fire' conditions using second-order finite element analysis techniques incorporating non-linear material properties. The basis of the study was to examine the energy absorption capability of the floor plate assuming impact from the whole of the floor above falling as debris. The floor plates in question comprised:

- 125mm thick composite floor slab;
- supported on 457mm deep secondary steel beams;
- secondary beams supported by a concrete core at one end and a 900mm deep perimeter beam at the other;
- perimeter beams span 24m and have full continuity with the substantial supporting megacolumns.

The studies showed that the 'weak link' in the ability of the floor to absorb energy was the secondary beam to core wall connection. This is despite such connections being designed to resist tying forces prescribed in the Hong Kong codes. The lack of ductility (rotational capacity) of the connection effectively limited the plastic (i.e. energy absorbing) deformation of members elsewhere in the floor (Fig. 5).

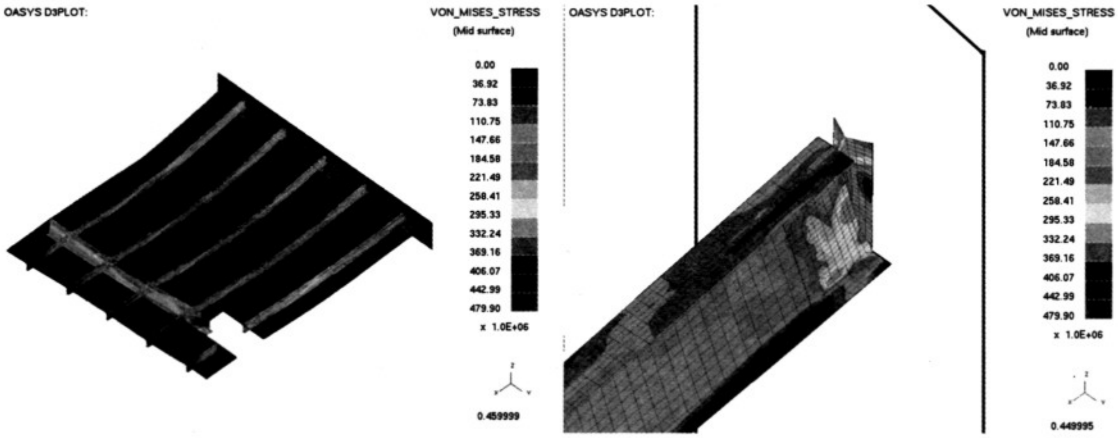

Fig. 5 Non-Linear Analysis of Floor Plate

It is interesting to note that at the point corresponding to the failure of the secondary beam to core wall connections, the additional load supported by the floor in its deformed state was equivalent to a state pressure of 30kPa – or approximately seven times the design live load under normal conditions. Despite this, the energy absorbed by the floor was only just sufficient to resist the kinetic energy of the floor above impacting on the floor under consideration. The study showed that, by modifying the detailing of the connection between the beams and the core, the total energy absorption for the floor plate, in term of resisting debris impact from the floor above, increased by 20%. The modifications investigated included the following (Fig. 6):

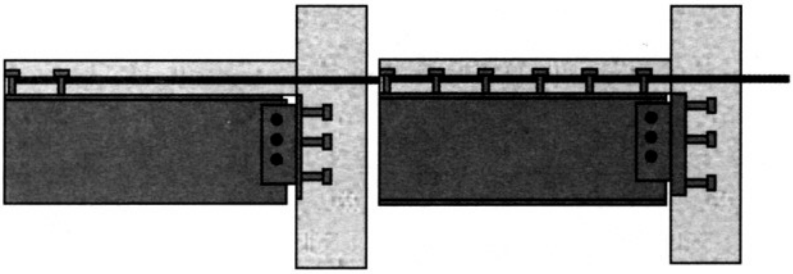

Fig. 6 Beam to Core Connection on left has increased ratation capacity

- Larger gaps between beam ends and the face of the connection to permit greater rotation.
- Thinning of the cast-in end-plate from 20mm to 16mm – thereby promoting end-late deformation.
- Omitting shear studs at the ends of the beam to permit improved straining of continuity reinforcement.

These modifications are quite compelling in that the cost of the connection is effectively reduced whilst the rotation capacity is improved.

The floors of buildings in Hong Kong comply with the requirements of the tying force requirements in British codes. Here, the connection of the floors to the perimeter structure are designed to resist prescribed tying forces. This requirement was prompted by the collapse of Ronan Point in 1968. Ronan Point was constructed from pre-cast concrete vertical panel elements. A gas explosion occurred on the 18th floor, blew out the perimeter structural panels, resulting in the collapse of the floors above in that quadrant of the building. The falling debris impacted the floors below, resulting in the failure of the majority of floors below. The incident was identified as a progressive collapse, the extent of which was disproportionate to the cause and prompted the introduction of specific legislation to prevent a recurrence of the tragedy.

The subsequent requirement for tying forces as prescribed in British Standards is intended to prevent the blowing out of perimeter structural panels in such a similar situation. When applied to framed structures, the prescribed tying forces were also considered to offer a 'catenary resistance' to floors in the event of key element removal. Fig. 7 shows a photograph of a blast damaged building which, whilst obviously having suffered a significant traumatic event, did not collapse disproportionately, and highlights the intention of the requirements. However, the requirements of tying force resistance is relatively simplistic in that a static load is derived and applied in the connection design. The key issue is that the requirements are not complimented by any ductility, or rotational capacity considerations. As can also be seen from Fig. 7, it is evident that rotational capacity of connections at the supports is also required, in addition to the tying requirement, in order to allow the floors to act in this manner. All too often, the detailing necessary to satisfy the codified static tying force requirement results in connections with reduced rotational capacity – effectively reducing the performance of the floor system. The authors suggest that this is a significant deficiency in the present codes. The authors advocate the adoption of a more considered dynamic robustness approach as has been performed on the floors of Two IFC.

Fig. 7 Ductile Failure of Floors showing hinges and tying action

4. Building Egress

One of the key recommendations following 9/11 is that measures are adopted to minimize the time taken for occupants to egress buildings. Studies were conducted to compare the escape requirements in Two IFC when applying Hong Kong escape requirements, compared to those of NFPA. Table 1 shows the comparison. It is evident that the requirements in Hong Kong are more onerous. This is due to the requirements being largely based on a simultaneous evacuation philosophy resulting in wider, and more numerous, exit stairs. Furthermore, it is a requirement in buildings in Hong Kong that refuge floors are provided every 25 storeys - as adopted in Two IFC. The merits of refuge floors are as follows:

- A physical barrier is provided in stairwells every 25/F. This forces people to egress on to the refuge floor and continue down the building via a different stairwell. Such measures prevent the chimney stack effect of smoke ingress throughout the height of the building via continuous stairwells.

- The refuge floors are naturally ventilated to act as a resting point for those egressing from the building.

- It provides a control point for assembly of fire fighters entering up the building.

Two IFC contains two fireman's lifts which run the full height of the tower. They serve fire and smoke protected lobbies at all floors and are powered from emergency generators. These lifts, a prescriptive requirement under the Hong Kong Code, provide rapid access to the fire from Fire Fighters and permit quick egress of disabled occupants from the building.

Although not specifically considered in the case of the Two IFC studies, the use of lifts to facilitate general egress is an issue which is gathering momentum in terms of achieving the goal of getting people out of a tall building as quickly as possible.

Table 1. 420m Office Building – Comparison of HK and US Codes

Egress Issues	HK Codes	NFPA 101 (2000)
Occupancy Load per floor	232	232
Common Path Distance	18m	23m
Max Travel Distance	30m	90m
Number of Escape Stairs Required	4	2
Minimum width Escape Stairs	2x1.2 / 2x1.5m	2x1.1m

To this end, Arup have undertaken real, and simulated, evacuation trials using lifts as a means of egress from a forty storey building in Europe. The aim of the studies was to investigate the potential improvement in egress time in the event that lifts were used as part of the emergency evacuation strategy. Presently, there are no codes around the world which permit the use of lifts in emergency egress situations. However, it is evident that they do offer an additional means of escape in instances where an extreme event is imminent and rapid simultaneous evacuation is warranted.

The studies required participants in the building to respond to a simultaneous evacuation alarm and egress through the escape stairs only. The trial was then repeated with the participants being given the choice of either egressing via the stairs or the lifts. The lifts had been previously been installed with software which forced them into an 'express down' mode when 70% full. Interestingly, in this phase of the trial, 50% of the participants used the lift whilst 50% used the escape stairs. The overall findings were that in the trial, in which the lifts were used as part of the egress, the evacuation times were halved compared to that in which the stairs only were used.

It is recognized that, as far as the adoption of lifts in evacuation situations is concerned, there is much continued work to be done to fully justify the approach and the overall safety to evacuees. Nevertheless, this one off study does demonstrate the enhancements in evacuation speed that can be achieved. It is of note that Arup Fire are presently undertaking studies for the authorities in Hong Kong to explore the use of lifts in such egress situations.

5. Discussion

The findings reported herein are specific to studies undertaken to examine the ability of buildings to resist the initial stage of an extreme event. If the building can indeed survive such an event, then it is necessary to consider the interaction of the performance of the damaged structure in conjunction with fire. However, it is the opinion of the authors that many tall buildings around the world would not be able to resist the detrimental effect of the initial damage due to a lack of structural robustness. The studies reported above are intended to inform designers of appropriate methods of evaluating the robustness of buildings prior to definitive recommendations becoming available.

Conclusions

This paper describes studies performed on the Two IFC building in Hong Kong. The findings from these studies suggest that the building possesses a higher degree of inherent structural robustness compared to other buildings around the world. In addition, it is evident that the present means of escape requirements in Hong Kong are more conservative than those applied elsewhere with the potential to reduce egress times.

The paper has identified a number of recommendations for the enhancement of building performance in response to extreme events. This includes highlighting the importance of consideration of dynamic robustness in addressing structural robustness. Also identified are considerations of the structural form and the potential use of lifts in accelerating building egress in emergency situations.

References

Institution of Structural Engineers (2002), 'Safety in Tall Buildings, and other Buildings with large occupancy'. The Institution of Structural Engineers

Gibbons C., Lee A.C.C., MacArthur J.M and Wan C-W.(2002) 'The Design and Construction of Two International Finance Centre Hong Kong Station', Advances in Building Technology Conference Hong Kong; Dec 2002, pp.703-712.

Hong Kong Buildings Department, Code of Practice for the Provision of Means – of Escape in Case of Fire, 1996.