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Structural Fire Design and Approval of a 156m Tall High-End Residential Building in Abu Dhabi

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Dr Florian Block has gained his Dipl.-Ing. degree in 2003 in structural engineering from the University of Technology in Darmstadt, Germany. Followed by a BuroHappold Engineering sponsored PhD at the University of Sheffield focused on structural fire engineering.

Since 2006 Florian is working for BuroHappold initially in Leeds, UK and now in Frankfurt a.M., Gemany and is leading a team of structural fire engineers delivering international projects focusing on sports stadia, commercial and tall building. In his work Florian strives to combine the latest research findings in structural and fire engineering with high level strategic approaches and advanced analysis techniques.

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Felix Summers is a Structural Engineer based in the United Kingdom. Since joining BuroHappold Engineering in 2012, he has worked on a variety of stadia, commercial and transportation projects. Over a two year design phase, Felix completed the analysis and design of a substantial high-rise development in Abu Dhabi. Meeting the architectural aspiration for open air public realm space at the base and within the height of the tower involved the development of a complex stability system. This combined a braced exoskeleton with long span portal frames, avoiding the need for a central stability core.

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David joined the BuroHappold Fire Engineering Team in 2010 as a Senior Engineer in the London office having spent 5 years at Jeremy Gardner Associates. David is a Chartered Fire Engineer now based in Dubai developing innovative fire engineering solutions for buildings in the UK, Middle East and Asia.

In his current role as Associate at BuroHappold David leads projects throughout the Middle East and Asia and helps to develop BuroHappold Fire Engineering in these Regions. David has led the fire engineering design on a wide variety of projects right from conception and Local Authority approval to completion on site.

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Abstract

The tower has an external mega-frame with four story long exposed bracing members.

A high quality finish to the diagonals was critical and 3h fire rating made the use of normal fire protection difficult. Hence, a performance-based design was used.

A number of realistic design fires were developed and the temperatures of the diagonals were calculated using a new approach. The temperatures of the unprotected diagonals were so high that they could fail.

The effect of thermal expansion of the diagonals on the frame was tested using ETABS. Then the heated diagonals were removed and the structure checked for over-stresses and deflections. All analyses showed that no global collapse due to a diagonal failure would occur allowing unprotected bracing members.

After a thorough 3rd party review and meetings with the head of Civil Defence the design was approved making it the first of this type and scale in Abu Dhabi.

Keywords: ETABS, External Mega-Frame, New Heat Flux Calculations, Structural Fire Engineering

Introduction

While a performance based design approach has been adopted widely in the UK and some other parts in the world, it is a relatively new approach in the Middle East particularly in Abu Dhabi. Therefore this paper serves to present a case study which summarise the structural fire design and approvals process of a 156m tall high-end residential building on the Maryah Island in Abu Dhabi, UAE. Among the special features, the architects are keen to express, is the external steelwork, which forms part of the mega-frame with large external diagonal steel tubes. The client's intention is to have a very high quality and low maintenance finish to the external steelwork as they are very visible from the apartments. This aesthetic requirement in combination with the aggressive sea side climate and the prescriptive 3 hour fire rating would have made it very difficult to use standard fire protection products and it was decided to follow a performance based methodology to design the external mega frame to meet the safety and aesthetics requirements.

Building Description

Building EW 11 is the first building in a phased residential develop at Maryah Plaza and is one of three similar residential buildings that are planned for this development phase (see Figure 1). A key architectural feature of the building is an expressed structural frame comprising perimeter columns that are set outboard of the building facades with exposed bracing structure between columns and connected every four levels. The building comprises three basement levels below ground, three levels above ground up to a podium. The residential tower has 31 levels above podium.

The design proposes a unique structural system of 4 storey modules with 1 transfer floor per 4 stories and 3 lightweight 'module' floors above with no internal stability core. This allows internal columns in the residential accommodation to be no larger than 203UC sections and, for the given building height, the opportunity to add 2 additional levels of residential accommodation due to the reduced structural depth required. Vertical load in the building is transferred to 14 mega-columns (10 on the perimeter and 4 internally) via a series of primary and secondary transfer beams. Lateral stability is provided by 2 systems: a concentrically braced frame system in the E-W direction with 20m long 559mm CHS braces in 3 bays between the exterior columns and moment frame system in the N-S direction (See Figure 2).

The structural function of the bracing members is to resist lateral loads induced by wind load and seismic events only. They provide no resistance to gravity loads. The bracing members will comprise 559mm diameter steel tubes with wall thicknesses between 25mm and 32mm. The main building façade line is set 3.5m back from the centre line of the perimeter columns. On a typical floor external balconies project 2.0m from the façade line. Every four floors the balconies project 3.5m and engage with the perimeter columns.

At the time of undertaking the design the building superstructure comprises a steel frame with composite concrete floor slabs however this is currently being redesigned as a concrete frame, which will maintain the external steel diagonals.

Applicable Building Codes and Design Standards

As required by Abu Dhabi Municipality, the structure is being designed to the Uniform Building Code [International Council of Building Officials 1997] and the fire safety design was in accordance with NFPA 101 [NFPA 2012a], the requirements of the Abu Dhabi Civil Defence authority (AHJ) and in accordance with the fire strategy. For the performance based assessment of the fire performance of the external bracing elements it is required to use structural and fire engineering calculation methods which are not provided for in either of these codes but have been extensively used around the world, especially in Europe and the USA, to justify a safe fire performance of external structures without the need for applied fire protection. This design approach is fully adopted into the structural Eurocodes (EN1991-1-2 [CEN 2002a] and EN1993-1-2 [CEN 2005]) and has also been published by the American Iron and Steel Institute [AISI 2005].

Fire Rating required by the Codes

Due to the height of the building exceeding 128m the required fire resistance rating of the structural elements is as defined in Table 1.6 within the UAE fire and life safety code [Ministry of Interior 2011], and NFPA 5000: 2012 [NFPA 2012b]. With the building being sprinklered, the structural frame is required to achieve a fire rating of three hours.

Structural Fire Engineering Approach

Due to the location of the external bracing elements outside of the façade, the innovative design of the building and the expected worst case realistic types of fire it was seen as the authors duty of care as professional engineers not just to follow the prescriptive design guidance, based on the standard furnace fire and fire protection materials that are only certified in accordance with the standard furnace test, but to undertake a performance based structural fire engineering assessment to demonstrate a safe and economic solution.

A performance based design needs to get the approval of Abu Dhabi Civil Defence, which relies on a detailed peer review of the design by a House of Expertise appointed by the Civil Defence authority therefore a two stage approach was used with the following steps:

Stage 1

- Define methodology
- Define acceptance criteria
- Define fire scenarios
- Define Fire Limit State loads
- Agree input variables with House of Expertise

Stage 2

- Perform heat transfer analyses from fire to structure
- Calculate steel temperatures
- Calculate response of structural frame
- Compare structural response with acceptance criteria
- Submit detailed report to HoE
- Submit final report to Civil Defence for approval

Figure 1. Architectural render of the three towers (Source: Rogers Stirk Harbour + Partners)

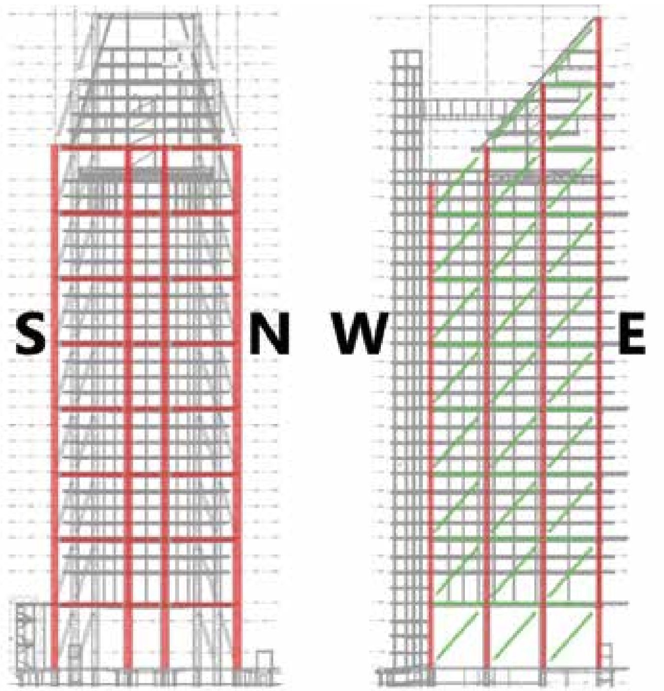

Figure 2. Structural system schematic (Source: BuroHappold Engineering)

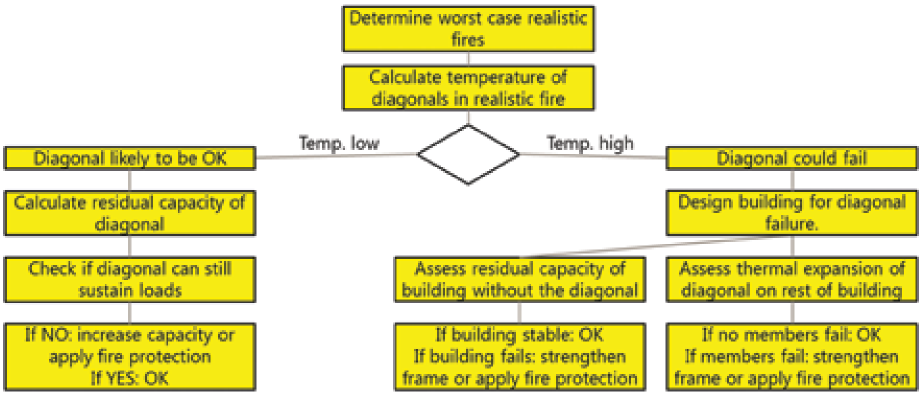

Figure 3. Design flow-chart (Source: BuroHappold Engineering)

Stage 1 - Methodology, Design Fires and Acceptance Criteria

As part of the performance based design approach it was necessary to determine and agree the methodology, the design fire scenarios and the acceptance criteria with the 3rd party reviewer acting as House of Expertise for the Abu Dhabi Civil Defence and other stakeholders.

Methodology

The methodology that was followed for this structural fire engineering assessment is illustrated in the flow chart given in Figure 3. The idea is that after establishing the worst case design fire scenarios and the assessment criteria the temperatures of the steelwork diagonals are calculated and a decision has to be taken if the temperatures are low enough that the bracing elements are likely to be able to sustain the loads for the full duration of the fire or are likely to fail at some point during the fire. From that decision onwards two separate approaches can be followed either to demonstrate that the structural member can sustain the function in the building that it has been allocated, or showing that the member is redundant when it fails and that in the process of failing the thermal expansion of the heated member does not damage the rest of the structure.

Definition of the Design Fires

In order to determine the most severe realistic fire scenario three different scenarios have been considered. The first scenario was a fire in a typical apartment ignoring the internal non-fire rated walls. The second scenario was a room in an apartment that has an opening to the external bracing members - assuming that the internal non-fire rated walls will remain intact for the full duration of the fire. The third scenario was a car fire at podium level adjacent to the lowest bracing members.

To predict the fire scenarios for the apartments the well-known and extensively validated software package OZone [Cadorin et al. 2001] has been used. The software has been developed at the University of Liege, Belgium and is based on the principles of a zone model. Furthermore, Ozone can predict flashover and breakage of windows based on a compartment temperature criteria and therefore, automatically change the amount of ventilation available to the fire, which is an important feature to predict a realistic fire development. However, since the actual breakage behavior of the glazing is very difficult to predict accurately a parametric study has been performed to investigate effects of different percentages of glass breakage at different temperatures. A total of 10 cases were studied and the worst case fire scenario in terms of highest compartment temperature and longest duration was found to be the 3 bedroom apartment in the case where the internal non-fire rated walls in restricting fire growth are ignored. The evolution of mass burning rate and gas temperature with time are shown in Figure 4 for this scenario.

As it is possible to drive underneath the diagonals at podium level of the building (see Figure 5) a car fire has been assumed with approximately 1m vertical separation from a bracing member. Due to the long distances between the points at which the bracing members are in the vicinity of the podium floor, it is very unlikely that more than one diagonal could be affected by a car fire. The heat release rate (HRR) of an MPV on fire is taken as an appropriate, conservative design fire. The data relating to this design fire is taken from Test 8 of the BRE report BD2552 [BRE 2009]. A safety factor of 1.2 is applied to both the heat release rate (HRR) and duration of the design fire – increasing the total thermal energy produced by a factor of 1.44.

Acceptance Criterion

The structural fire engineering assessment is specific to the external bracing members which provide lateral stability against wind and seismic loading. Therefore the acceptance criterion adopted was that the global stability of the building is maintained for the full duration of a worst case realistic fire scenario under accidental fire limit state loads. This means that local damage to the bracing members directly involved in the fire is seen as acceptable as long as this does not negatively affect the overall structural performance of the building and that a progressive collapse does not occur.

Fire Limit State Loading

Fire is treated as an accidental load case. The structural design of the project was based on AISC 360-10 [AISC 2010] and, therefore, the partial safety factors provided in this code are adopted here. However, the load combination for fire given in AISC 360-10 does not consider

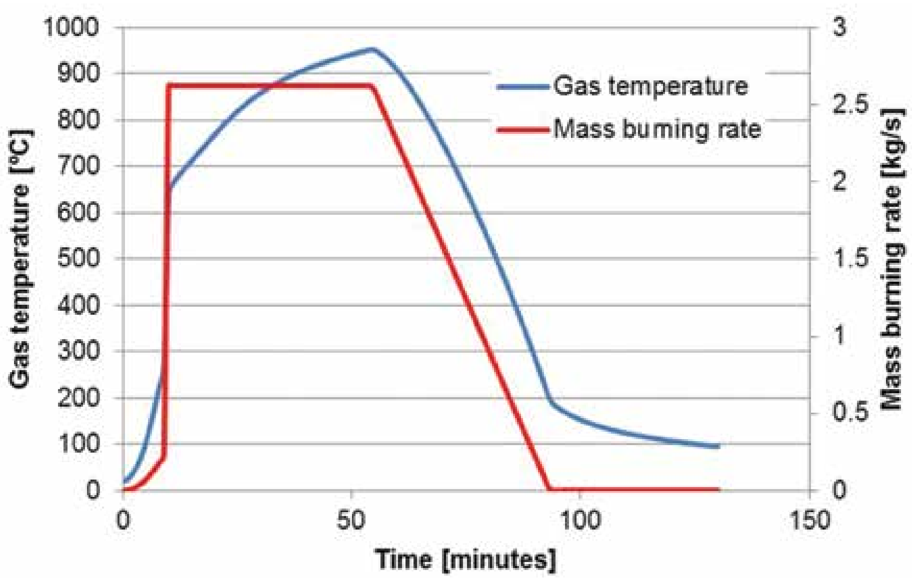

Figure 4. Main results of the worst case realistic compartment fire (Source: BuroHappold Engineering)

Figure 5. Diagonals interface at podium level (Source: Rogers Stirk Harbour + Partners)

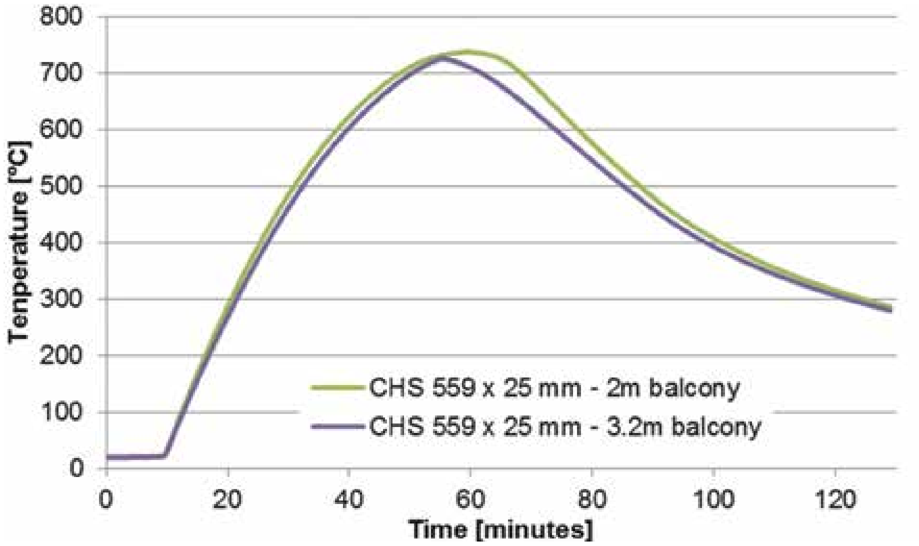

Figure 6. Temperature – time profile within external bracing due to compartment fire (Source: BuroHappold Engineering)

wind loading under fire conditions, but EN1990 [CEN 2002b] considers wind as part of the fire design, and since wind load is one of the major design factors for the diagonals, it has been considered with a partial safety factor of 0.2:

$$([0.9 \text{ or } 1.2] \text{ x } D) + ([0.5 \text{ or } 0.0] \text{ x } L) + ([0.2 \text{ or } 0.0] \text{ x } W) + T$$

where:

- D = nominal dead load (0.9 only to be used if D is beneficial);
- L = nominal occupancy live load;
- W = nominal wind load (0.0 only to be used if W is beneficial); and
- T = nominal forces and deformations due to the design-basis fire.

Earthquakes are a relevant load case in Abu Dhabi, however they are not considered in the AISC 360-10 load combination recommended for the fire design of buildings. For the EW11 building wind and earthquake are similar in that lateral loads of approximately the same magnitude are introduced into the building structure. However, the design earthquake adopted in the design has a probability of occurrence of 1 in 475 years and the wind loading a probability of occurrence of 1 in 50 years. Therefore, designing the structure for 20% of the wind loading in the fire case is also seen as sufficient for earthquakes.

Stage 2: Heat Flux and Steel Temperature Calculations

After the agreement of the different relevant input parameters with the House of Expertise to minimize the approvals risk after the completion of the detailed design analysis, the second stage was started with calculating the steel temperatures and sub-sequentially the structural response modeling.

Calculation approach for steel temperature

For the current project a 1-D Lumped Heat Capacity method has been initially favored as the temperatures of the steel braces were found to be higher than the initially assumed failure temperature; no more detailed analysis of the non-uniform temperature profile of the cross section was conducted. However, if the steel temperatures would have been low enough so that the building could have been design in such way that the diagonals would remain in place, the non-uniform temperature profile would have had to be considered in the structural analysis. Like this the thermal curvature and the resulting increase in P-Delta effects would have been taken into account.

Heat flux calculations

The heat flux experienced by an external steel member due to a compartment fire, can be determined using an approach originally developed by Law and O'Brien. This approach was published in the US by the AISI in 1979 [AISI 1979] under the name of Fire-Safe Structural Steel, A Design Guide. It is also described in the SFPE Handbook [SFPE 2002], which refers to the calculation approached in the EN1991-1.2 Annex B and G [CEN 2002a] and EN1993-1.2 Annex B [CEN 2005].

This design approach is generally well developed and validated. However it has some short comings, which will be addressed for building EW11. Among the shortcomings is that it assumes a steady state fire that is burning for an infinite amount of time rather than a realistic fire scenario. In addition no proper consideration of the effects of large balconies is included. Uniform heating of the steel elements is also assumed and therefore, any thermal bowing introduced by hotter parts of the steel elements on the side directly facing the fire is ignored. The shortcomings are addressed by updating the approach [Block et.al., 2014]. The resulting steel temperature profiles for a CHS 559 x 25mm bracing element located external of the fire compartment in question are shown in Figure 6 for differing balcony dimensions. The bracing adjacent to the short balcony (2m) is shown to be higher than the one with the larger balcony and reaches a peak steel temperature of 725°C.

The localized fire approach given in EN1991-1-2 Annex C [CEN 2002] has been used to calculate the heat flux from the car design fire to the bracing elements. It is based on the Heskestad Method and allows the calculation of the radiation and convection received by the external bracing elements.

The resulting temperature of the bracing subjected to a localized vehicle fire is shown in Figure 7. The bracing is engulfed in the flame for long periods of time due to its proximity to the source of the fire. As a result, its peak temperature is predicted to approach 900ºC over the course of the fire, which corresponds to the bracing element having just 5-6% of its ambient strength remaining, according to AISC 360-10 [AISC 2010].

Discussion of Results

As it can be seen from Figure 6 and Figure 7 it is possible that due to the worst case realistic compartment fire in the residential parts of the building and the vehicle fire the rise in temperature of the member, is so significant that it is very likely that the structural bracing would fail. Therefore, the decision was made to follow the route of demonstrating redundancy and a safe failure of the bracing members.

Stage 2: Structural Response Calculations

As explained in the methodology section of this paper, to demonstrate the redundancy of a structural member, two different analyses are required. The first one is to test if the bracing member in question can be removed without causing a progressive collapse under fire limit state loads; the second analysis is to test if the heating and thermal expansion of the member in question would cause damage to the surrounding structural frame and could therefore be leading to a progressive collapse of the structure before the heated member is failing.

A series of global frame analyses have been conducted using the ETABS model (see Figure 8) used by the structural engineers under the Fire Limit Load cases by heating a number of different external bracing elements separately in order to analyze the stiffness of the global frame that would be introducing axial forces into the bracing members.

Thermal Expansion Analyses

Furthermore, the global analyses will also be used to assess the rest of the structural frame, which is not exposed to the fire, to see if the thermal expansion of the heat bracing element would cause any significant structural damage remote from the fire. . A single element analysis would not be able to take these into account.

Figure 9 shows the 5 locations that have been assessed during the thermal expansion analyses. These locations have been determined by choosing members that, when heated, are adjudged to have the most adverse effect(s) on the surrounding structure. The assessment followed the steps below:

- Analyze the base line structure to identify the worst case bracing members to be tested.
- Calculate the tensile and compressive capacity of the diagonals at increasing temperatures based on the equations provided in AISC 360-10 [AISC 2010] for buckling of members at elevated temperatures.
- Heat the selected critical members individually with increasing temperature steps in the global ETABS model taking into account the reduced material stiffness.
- Comparing the forces in the diagonals with the calculated capacities at the respective temperatures to determine if diagonal failure has occurred.
- Checking the utilization of all other members to see if other members are likely to fail due to the thermally induced forces in the frame.

Results of the analysis have shown that the maximum utilization of the other structural elements such as non-heated diagonals, beams and columns are not exceeding 100%. Therefore, it was conclude that a thermally induced progressive collapse is very unlikely before the tested diagonals are deemed to fail so that the next step, the redundancy analysis is valid.

Redundancy Analyses

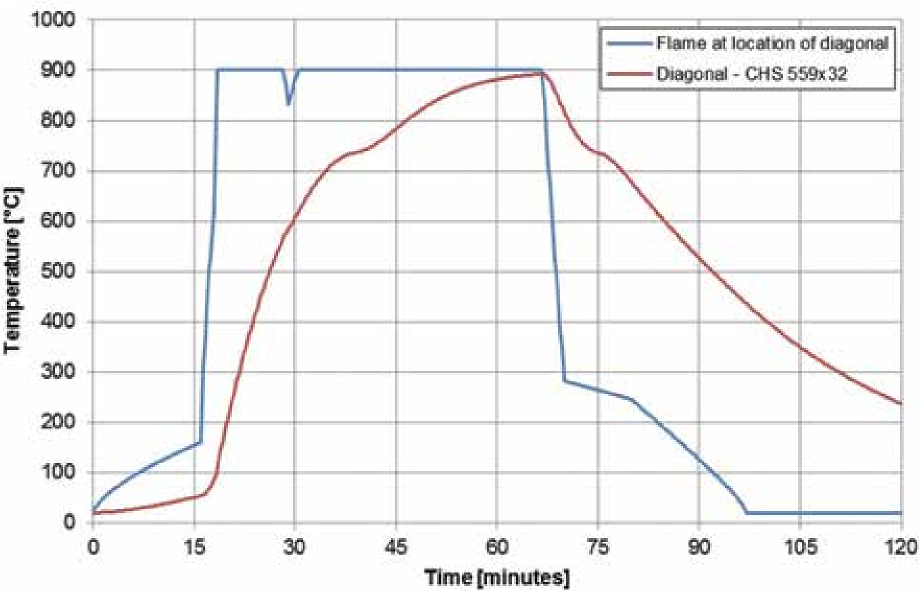

Figure 7. Flame and diagonal temperature 1m above the roof of the vehicle (Source: BuroHappold Engineering)

Where the resulting steel temperature of the bracing element reaches a level such that the strength and stiffness of the member are significantly reduced, a series of redundancy analyses were conducted. In these analyses the selected bracing members were removed from the analysis model in turn to assess if this would cause any global stability issues under fire limit state loading. Following analysis of the brace forces from the baseline model with no damage, Figure 10 shows the 6 locations that were subject to further study during this test, which are representative of the most highly utilized braces or those in positions where their removal might cause the greatest potential global instability.

Following removal of elements from the model the utilization in the remaining members under Fire Limit State loads does not exceed 100% in any case, meaning the structure maintains its global stability post-buckling of the assumed heated members. Furthermore, the vertical and lateral movements of the building were less than the movements expected during Ultimate Limit State.

Discussion of Results

The detailed Stage 2 analyses of the heat flux from the different design fires and the steel temperatures of the external diagonals have shown that it is possible that the external diagonals can be heated to temperatures high enough that they are likely to fail if not fire protected. However and the two sets of structural response calculations have shown that a fire induced failure of a diagonal would remain a local event without causing significant damage to the rest of the structural frame or even causing progressive collapse of the building. Therefore it could be concluded that the diagonals do not require fire protection.

Approvals Process

As it was touched upon earlier in the paper the Civil Defence approvals process in Abu Dhabi uses a system of preapproved 3rd party peer reviews to support the Civil Defence officials with fire engineered projects.

The Civil Defence (AHJ) approvals process in Abu Dhabi is outlined in a set of Plan Review Manuals issued by the Ministry of the Interior and the General Directorate of Civil Defence Safety and Prevention Department. These manuals give clear guidance on submission of fire strategy drawings and reports but give no guidance for the process of submitting an alternative performance based design solution. For this reason it was critical for the success of the project that the AHJ were engaged very early on in the design stage to inform them of the intention to carry out a performance based design and agree the design brief.

As this was one of the first projects in the UAE to propose the use of structural fire engineering the AHJ realised the lack of in-house expertise in this field and recommended that a 3rd party fire engineer be appointed on behalf of the client to review the performance based design elements of the building design.

With the 3rd party fire engineer engaged in addition to the AHJ the project team set about developing the performance based design proposals for the structural fire engineering as well as other design aspects which did not meet the prescriptive requirements of the UAE and NFPA Fire Codes. Through a series of design workshops involving the AHJ and the 3rd party fire engineer the design was developed and then peer reviewed by the 3rd party fire engineer to ensure that it was robust, considering all possible worst case fire scenarios, and that it followed the process and requirements outlined within NFPA 101 Chapter 5 for carrying out a performance based design.

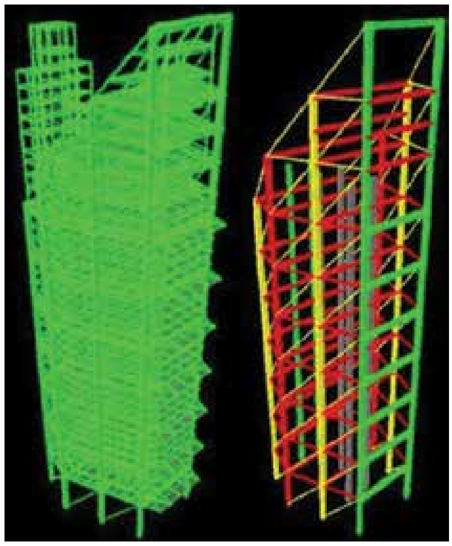

Figure 8. ETABS Structural FE model and stability members only model (Source: BuroHappold Engineering)

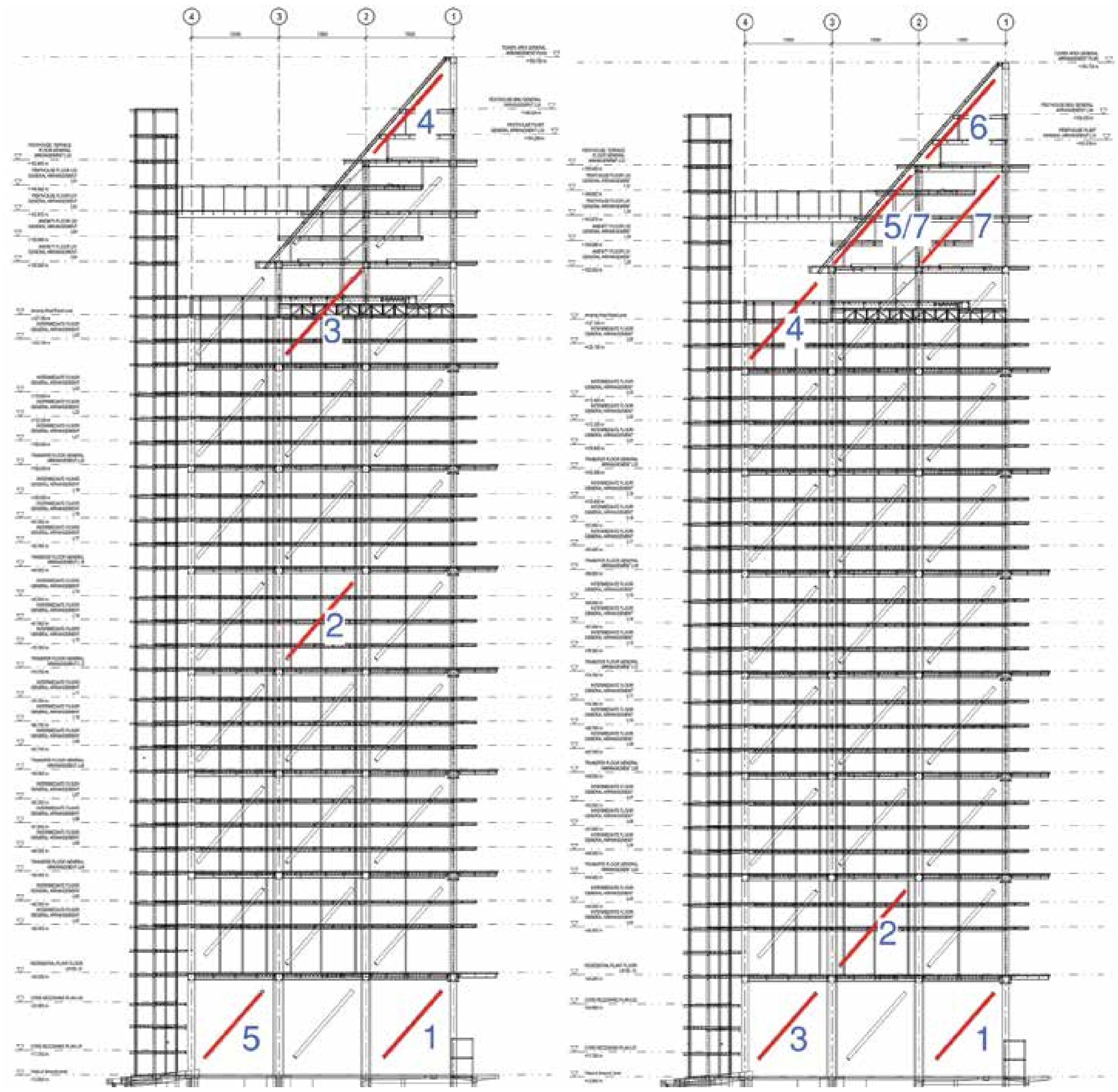

Figure 9-10. Diagonals subject to heating as part of the thermal expansion analyses (left); Diagonals removed as part of the redundancy analyses (right) (Source: BuroHappold Engineering)

Once the 3rd party fire engineered completed their peer review and issued their certification of the fire strategy and structural fire engineering report the final design was presented to the AHJ. Upon review of the final design the AHJ accepted the performance based design solutions and issued approval for both the fire strategy and the structural fire engineering report.

This marked a major achievement for the design team as the project was one of the first in the UAE to gain approval from the AHJ using a fully developed performance-based design fire engineered solution.

Conclusion

This paper summarizes the successful application of the performance based structural fire engineer process on a tall building in Abu Dhabi with external not fire protected steelwork, which allowed a safe and economic solution to the external diagonals that also satisfies the high finishes standard desired by the architects and the client.

As part of this project a number of new additions to the well know external steelwork approach were developed and it could be demonstrated how the ETABS model could be used for rigours redundancy calculations.

This process was only possible due to the open minded clients and the close collaboration between the structural fire engineers, the fire safety engineers, the structural engineers as well as the 3rd party reviewers and Civil Defences officials.

The hope for the future is that a project like the EW11 on the Maryah Island in Abu Dhabi will help to pave the way for further carefully and rigorously conducted structural fire engineering projects in the area allowing a safer and more economic buildings and fostering an understanding the fire should be seen as an equally important and quantifiable load case as wind, snow and earthquakes.

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