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Fire Damage Assessment of Reinforced Concrete Buildings Under Construction

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الملخص:
الخرسانة الانشائية الكثيفة وحديد التسليح هي مواد غير قابلة للاشتعال، ولكن تتأثر خواصها الفيزيائية والكيميائية عندما تتعرض للحرارة العالية، وهذه التغيرات في الخواص يجب ان تؤخذ في الاعتبار عند تقدير اضرار الحريق واثاره على قوة تحمل العناصر الانشائية. هذا البحث يهدف الى تقدير اضرار الحريق في برج خرساني تحت الانشاء بدولة الكويت وتصنيف استراتيجيات اعمال الاصلاح طبقا لتقدير اضرار الحريق، وقد تم التقدير وفقاً للاختبارات غير المتلفة (الفحص البصري واختبار مطرقة شميدت) والاختبارات المتلفة (اختبار القلب الخرساني) بالإضافة الى اجراء الحسابات الانشائية لمراجعة العناصر الانشائية المتأثرة بالحريق.
من نتائج البحث ان العناصر الخرسانية ذات العمر اقل من 28 يوم وقت حدوث الحريق تعرضت لأضرار جسيمة تطلبت ازالتها، وبصفة عامة فان الخرسانة التي تعرضت لدرجة حرارة اعلى من 300 درجة مئوية تعرضت لأضرار معتبرة، وكذلك فقد تبين ان تأثير الحريق كان محدوداً على امان الكمرات والبلاطات مقارنة بتأثيره على الاعمدة التي كانت العناصر الاكثر تأثراً بالحريق نتيجة النقص الكبير في مقاومة الضغط ولذلك فان أداء الاعمدة له كبير الاثر على امان المباني الخرسانية في الحريق، كما تبين من الاختبارات ان الحريق لم يقلل من مقاومة الشد لحديد التسليح.
طبقاً لنتائج البحث، فانه يوصى بتصميم الكمرات والبلاطات على اجهادات ضغط منخفضة واتباع كل المتطلبات الواردة في كود التصميم المتعلقة بالديمومة ومقاومة الحريق وخاصة متطلبات الاعمدة، وكذلك يجب ان يشمل تقدير اضرار الحريق كل عناصر المنشأ حتى العناصر ذات الاضرار المرئية البسيطة، بالإضافة الى تامين الجودة قبل البدء بأعمال الاصلاح مع الاخذ بالاعتبار ان طريقة الاصلاح المناسب والاقتصادي تنتج من اجراء التقدير الفعلي لأضرار الحريق.

Abstract

Dense structural concrete and reinforcing steel are essentially non-combustible materials. however, the physical and chemical properties are affected when exposed to elevated temperatures, changes in properties should be considered when assessing fire damage and its effects on the load carrying capacity of structural elements. This research aims to assess fire damage in concrete tower under construction in the state of Kuwait and provides a classification of remedial works strategies according to the assessment of fire damage. The assessment of fire damage for the building was carried out through non-destructive tests (visual inspection, Schmidt hammer) and destructive test (concrete core test), in addition to the Structural calculations check on the affected concrete members.

It can be concluded that concrete members younger than 28 days at the date of fire were suffered from severe damage. Generally, concrete exposed to temperature higher than 300^0c suffered from significant loss of strength. moreover, it can be deduced that there was a minor effect of fire on safety of slabs and beams compared with columns which were the most affected members by fire due to excessive loss of compression strength, so the performance of columns has a significant impact on safety of reinforced concrete buildings in fire. it’s concluded by test that fire didn’t cause losses in tensile strength of reinforcing steel.

According to the research conclusions, it’s recommended to design beams and slabs considering low compressive stresses and to follow all requirements of design code concerning durability and fire resistance especially those for columns, also the assessment of fire damage should include all structure elements, even the elements which have minor visible fire damage. In addition, the quality assurance should be planned prior to start of any repair works, considering that a proper, cost-effective repair methodology is attributed to accurate assessment of fire damage.

1. Introduction

The effect of fire on the concrete structure is described in terms of the concept of fire resistance, which is the period of time under exposure to a standard fire, the concrete mix proportions and constituents, the fire temperature and the concrete age.

Concrete is non-combustible material and poor thermal conductivity; However, the chemical and mechanical properties of concrete and steel are affected by elevated temperature. Since concrete can suffer significant stresses reduction. Large temperatures can reduce the compressive strength of concrete so much that the material retains no useful structural strength[1].

Requirements of durability and fire resistance must be considered in preliminary concrete design according to required fire rate, especially those for columns,

There are three methods of assessment of fire resistance: fire testing, prescriptive methods, which are rigid and performance-based methods, which are flexible. The real behavior of concrete elements is different from that indicated by fire testing because of the effect of cooler areas surrounding fire location.

A real case of a tower under construction subjected to fire on the formwork at the 8th floor roof, there was a strong westerly wind at that time. The fire started in the west side of the Tower and due to the elevated temperature and high wind speed, the fire spreaded from the west to the east side along 8th floor. Fallen pieces of burned shutters, and strong wind caused a fast spreading of the fire to the shutter of the 7th floor and to some places on the 6th floor.

The fire continued for more than 8 hours before firemen took control of it.

The cause of fire is unknown. Eye witnesses indicated that the fire started at the west end of the 8th floor roof shuttering. This floor was ready for cast on the following day.

2. Literature review

Fire resistance can be defined as the ability of structural elements to withstand fire or to give protection from it[2]. Fire Resistance Rating (or fire rating), is defined as the duration of time that an assembly (roof, floor, beam, wall, or column) can endure a “standard fire” as defined in ASTM E 119[3].

Dense structural concrete and reinforcing steel are essentially non-combustible materials; however, the physical and chemical properties are affected when exposed to elevated temperatures. These properties that need to be considered when assessing fire damage and its effects on the load carrying capacity of structural elements.

It is established by practice that the assessment of structural concrete after exposure to fire should take into consideration the following:

1. Duration and intensity of the fire
2. Temperature development within the structural members
3. Effects of the estimated temperatures on the engineering properties of Concrete and the steel

4. Feasibility of repairs to compensate for any unacceptable loss of structural performance or durability

Fire temperatures less than 300º C don't render concrete unusable, the mean compressive strength decreased by 30% after exposure to 300°C as shown in figure (1). Heating up to 300°C generated a relatively small amount of cracking, which did not cause any immediate loss of carrying capacity in compression because the slightly cracked concrete could work as a highly redundant structure[4]. According to the variation of the residual compressive strength, temperature of 600°C and above might be regarded as critical temperature range for the strength loss[5].
Residual compressive strength variations were studied in previous researches[6].

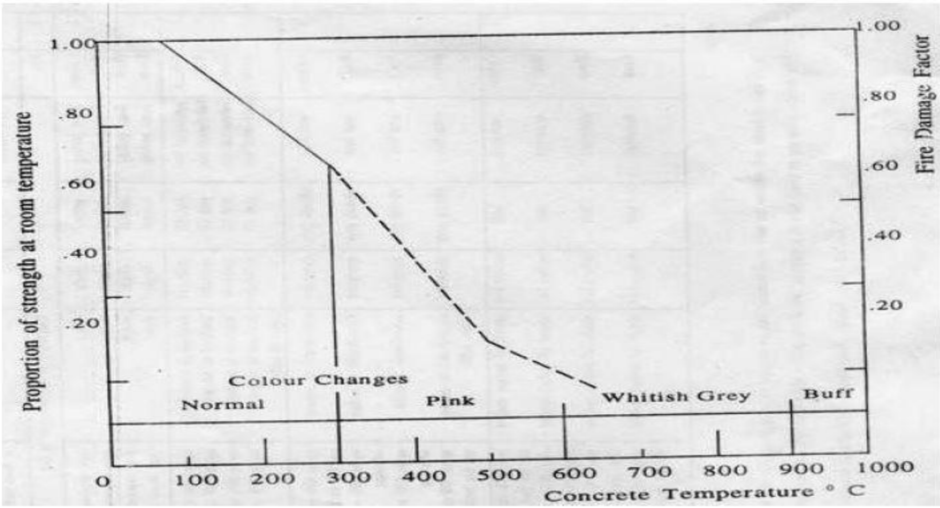

Figure 1 – Typical effect of heat on the residual compressive strength of structural concrete

As shown in figure (1), most of concrete elements discolor above 300°C. Thus, a visual inspection of the color change through the concrete gives an indication of the loss of strength.
Reinforcing Steel is affected by heat. the Reinforcing steel will be unaffected when the concrete at depth of cover subjected temperature up to 600^{o}c cover as shown in figure (2). Loss of ductility may occur after exposure to elevated temperatures.
Similarly bond strengths are affected by heat, bond strength of the ribbed bars reduced to less than 85% of the original value when the concrete at depth of cover subjected to temperature 300°C.

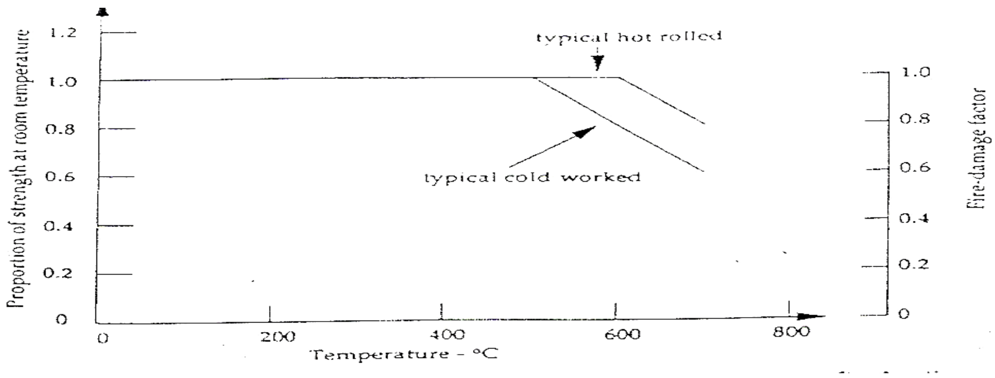

Figure 2 – Typical effect of heat on the residual strength of reinforcing steel

The effect of creep is considerable at around 400◦C since it can cause large deflections in concrete structural members[7] due to increasing in strain and reduction in concrete stiffness. Figure (3) shows the stress/strain curves for a type of normal weight concrete. For design purposes, the loss in concrete strength in temperature is generally varying with temperature required[8].

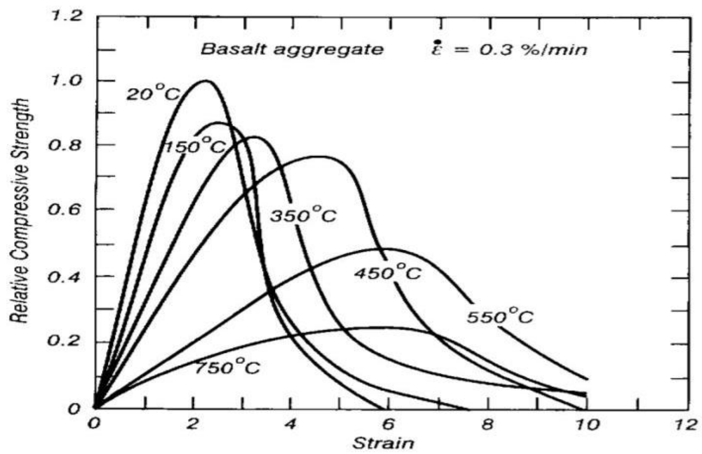

Figure 3: Relative stress / strain curves for dense concrete varying with temperature

Spalling (loss of surface material) is associated with elevated temperature. It's one of the most destructive effects of fire on concrete, it depends upon the type of aggregate used and fire temperature, with normal weight concrete much more likely to suffer spalling damage compared to light weight concrete[9]. spalling ranges from superficial surface damage to explosive blowout of large chunks of material. However, areas of concrete or masonry under high compressive stress may spall at relatively lower temperatures further away from the hottest regions. Spalled areas may also appear lighter in color than adjacent areas through exposure of clean subsurface material[10].

3. Objectives:

This research aims to assess fire damage in concrete tower under construction through non-destructive tests (visual inspection, Schmidt hammer) and destructive test (concrete core test), in addition to the structural calculations check on the affected concrete members. Also, it gives a knowledge on the overall strategy for the remedial works of fire damaged buildings. Finally, it provides general conclusions and recommendations for a proper assessment and repair.

4. Methodology:

The aims of research were achieved through following methodology steps:

1. Carrying out tests on the fire damage concrete to asset the concrete strength through visual inspection, Schmidt hammer and concrete core test.
2. Analysis of the effect of fire on the concrete members under 28 days age.
3. Structural calculations check on the affected concrete members (slabs, beams, columns and walls).
4. Classification of remedial works strategies according to the study results.

5. Site location & Building Description

The building is located at the State of Kuwait at about 12 Km to Kuwait City. The surrounding area South and East of the site is generally developed, while the areas North and West of the site consist of empty lands or buildings located at relatively far distance. The building has overall dimensions of 68.00m length, 33.50m width and approximately 82.00m high, it is designed to have Basement, Ground Floor, Mezzanine Floor and 19 typical floors (excluding roof), the basement level spread over the whole of the underside of the building. The building was designed for residential occupancy for all floors. The typical floor to floor height is 3.84m.

Expansion joints are provided at the center of the structure along the short axis of the building separating the building into two independent structure zones (zone 1 and zone 2). Separate elevator core is provided in each zone along the centerline of the building, one core accommodates four elevators.

Structural system

All structural members (Columns, walls, slabs and beams) of in-situ reinforced concrete construction, one or two way spanning solid slabs supported on beams are used as a structure system, beams have different depth and length which doesn't exceed 9 m. Figure (4) shows the structural system of the typical floor.

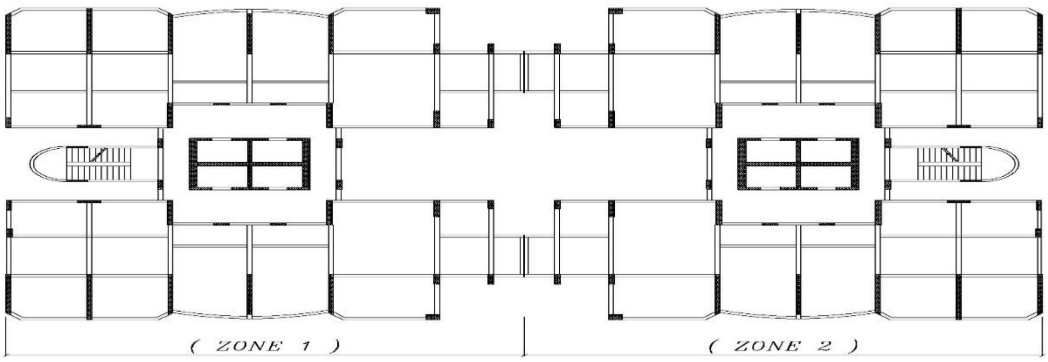

Figure 4: structural system of typical floor

6. Fire Description and Construction Status at Fire time

6.1 Cause of Fire and Fire Spread

The witnesses described their understanding of the fire as follows: -

Construction of the formwork and reinforcement of 8th floor roof slab Zone2 was underway. The fire started on the 8th floor roof slab formwork and progressively spread to the Zone2 columns and walls formwork, then down to the formwork supporting 7th floor roof slab in Zone 1 and Zone 2.

Wind was blowing from the West direction at the time of the fire.

6.2 Construction Status at Time of Fire

At the time of the fire, construction had progressed up to 8th floor roof, concrete age at fire time for the 6th, 7th and 8th floors shown in table (1).

Floor	Concrete age at fire time			
	Columns		Roof slab	
	Z1	Z2	Z1	Z2
8th Floor	1 to 3 days	3 to 10 days	----	----
7th Floor	14	19	8	12
6th Floor	34	39	27	32

Table1: Concrete age at fire time

As reported by the contractor, the slab formwork generally comprised of 18mm plywood supported on Doka sections at 300 mm c/c. A Doka system is also used for the columns formwork.

7. Fire damage assessment

Fire damage assessment in relation to the fire had been carried out through site investigation and structural calculations as follows:

7.1 Site Investigation

7.1.1Visual inspection

All areas subjected to the fire had been visually examined, we list the conclusion of this inspection for the considered structural items.

7.1.1.1 8th Floor (columns/walls)

The structure of 8th floor was under construction at the time of the fire and only partially completed, with approximately half of the columns and walls cast in Zone (1) between 1 to 3 days while all columns and walls cast in Zone (2) between 3 to 10 days as shown in table (1).

Damage to the columns and walls varies as follows:

- Spalling to about 80% of the surface of one face.
- Exposed horizontal bars in few cases.
- Smoke damage to the other columns.
- Buckling of the exposed Reinforcing steel.

Figures (5) & (6) shows fire damage to the columns / walls in zone (1) and (2) respectively.

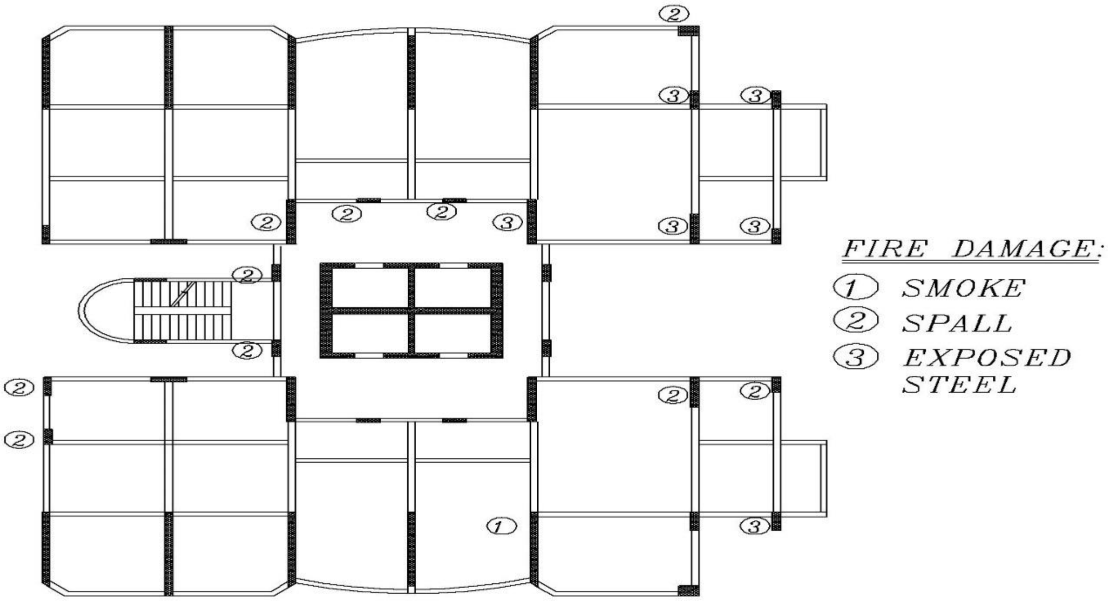

Figure 5: fire damage to 8th floor RC. columns/walls zone1

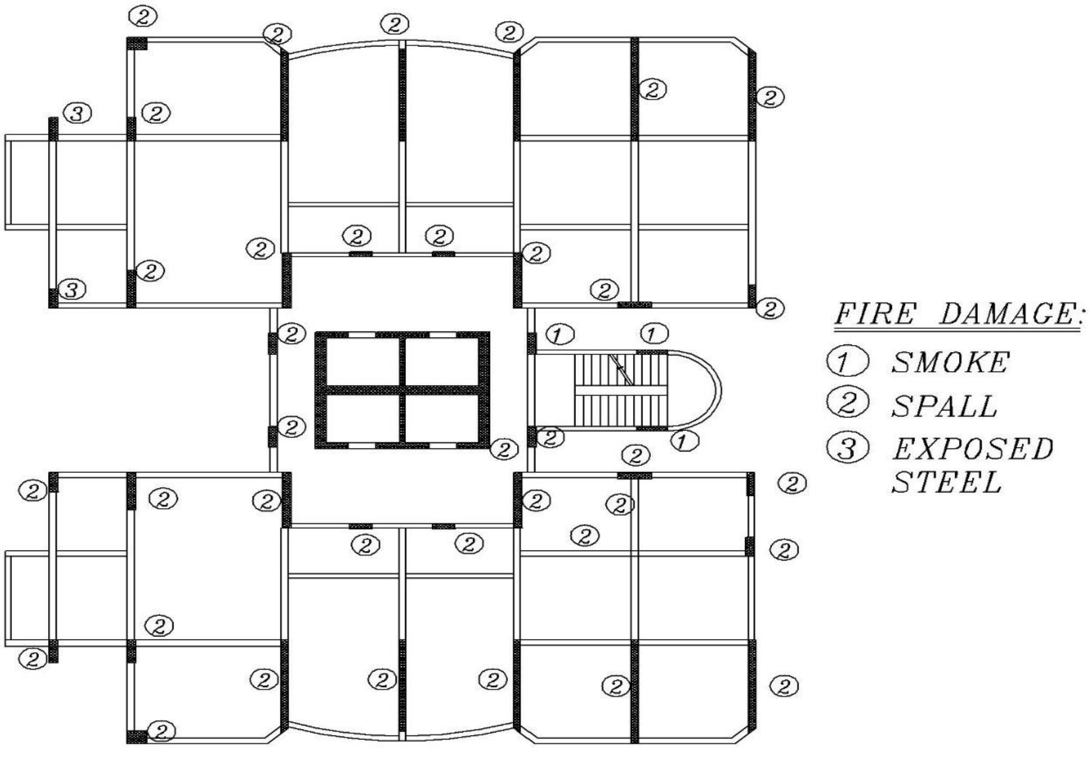

Figure 6: fire damage to 8th floor RC. columns/walls zone2

7.1.1.2 7th Floor (Columns and Roof Slab)

The 7th floor roof slab soffit has suffered significant exposure to the fire. Formwork was in place over the full extent of the soffit of the (Zone 1) slab at the time of the fire. The age of slab at the time of fire was 8 days old while columns and walls were 14 days old as shown in table (1).

The damage to the slabs of zone (1) varies significantly over the soffit as follows:

- Spalling concrete without exposed rebar under most of slabs.
- Exposed rebar in same slabs.
- Smoke damage to the rest of slabs.

The damage to the beams in zone (1) was less than the slabs while the main longitudinal reinforcement was not visible the damage to beams was observed as follows:

- Spalling concrete to small areas of the soffit and corners.
- Exposed stirrups at the sides and soffit of a few beams.
- Smoke damage to most beams.

The damage to the walls and columns in zone (1) was observed as follows:

- Localized spalling concrete in few case concentrated at the top of columns.
- Smoke damage to the other columns and walls.

Figures (7) shows fire damage to the 7th floor slab in zone (1).

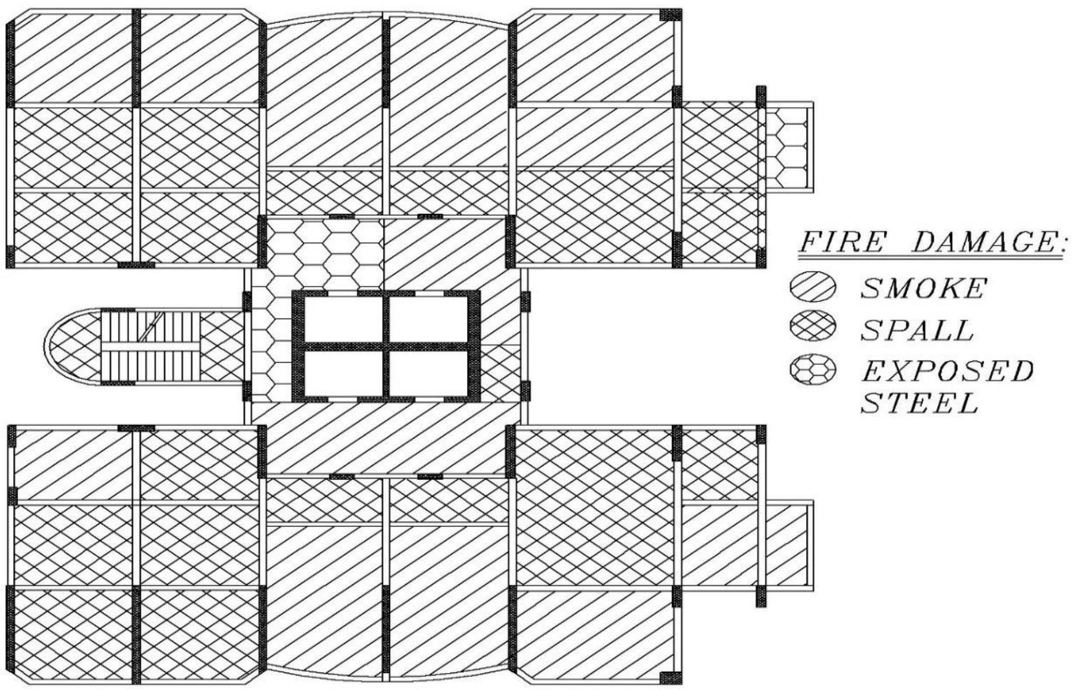

Figure 7: fire damage to 7th floor slabs zone1

The damage to the slabs in zone (2) is varied significantly between panels as follows:

- Severe damage to the slabs located at the north side of elevators core.
- Exposed rebar (two layers) at the same area.

- Spall and Smoke damage to slabs located at south of elevators core.
- No fire damage was observed to slabs located at southeast of elevators core.

The damage to beams in zone (2) was observed as follows:

- Severe damage to most beams located at the north side of elevators' core.
- Exposed stirrups at the sides and soffits of few beams.
- Spall and Smoke damage to some beams located at the south side of elevators core except southeast side.

The damage to the columns and walls in zone (2) was observed as follows:

- Spalling concrete to most of columns.
- Smoke damage near to top of columns and walls.

Figure (8) shows fire damage to the 7th floor zone (2)

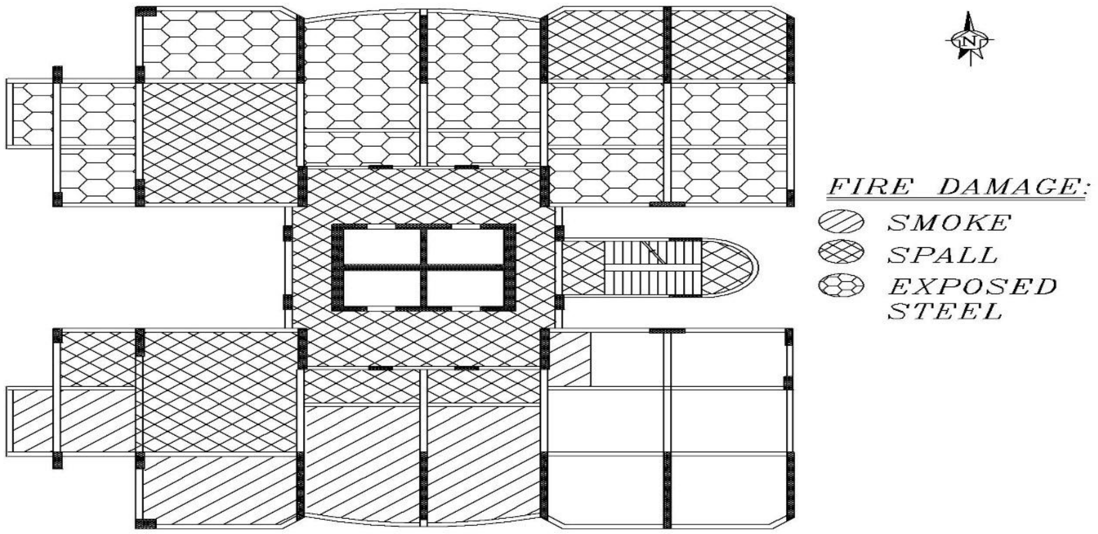

Figure 8: fire damage to 7th floor slabs zone2

7.1.1.3 6th Floor and Lower Floors

It was noticed that 6th floor and lower floors were not affected by the fire except some smoke damage particularly near staircases and lobby. Generally, the quality of construction for these floors appears to be good. However, core test was carried on slabs, beams and columns of 6th floor to check safety of concrete members.

7.1.1.4 Staircases and Elevator Cores

At 7th floor zone (1) the damage to elevator cores and staircases was observed as follows:

- Spalling on the flights, landing and supporting beams for staircases without exposed rebars.
- smoke damage to elevator cores.

At 7th floor zone (2), the damage to elevator cores and staircases was observed as follows:

- Spalling on the underside of stair flight, landing and supporting beams for staircases with some exposed rebars.

- Spalling on the elevators core was located at the internal and external faces near the top of wall with some exposed horizontal Reinforcing steel.

At 8th floor zone (1), the staircases and elevator cores had not been cast at the time of the fire, the starter bars and Reinforcing steel was in place. The Reinforcing steel of the elevators core and adjacent stair columns reinforcement was buckled.
At 8th floor zone (2), the staircases had not been built at the time of the fire while the damage to the elevator cores was observed as follows:

- Spalling on the internal and external face of both elevator cores.
- Exposed rebar on the internal faces.

7.1.1.5 External Damages

Smoke damage to the exposed concrete on the sides of some facade's beams was observed at 8th floor with spalling concrete on same locations, the facade damage was concentrated between 7th and 8th floor.

7.1.2 Removal of damaged concrete

The damaged and discolored concrete in some areas of the 7th floor roof slabs and beams were chipped away using a hammer and chisel to give a clear indication of the depth of damage, it was found that the damage depth equals to the concrete cover for the examined areas.

7.1.3 Schmidt Hammer tests

Schmidt hammer tests (59 Nos.) were carried out for slabs, beams and columns to give indication of the concrete strength, the numbers of the tests were distributed on the floors
as follows: 6th floor (11 Nos.) - 7th floor (18 Nos.) - 8th floor (30 Nos.)
Test results shows high concrete strength value if it is compared with the core test results for the same structural members, so only compression tests on cores were considered in the design check.

7.2 Laboratory tests

7.2.1 Compression core tests

Cores were taken from many locations where concrete was affected by the fire. Core tests (149 Nos.) are done. These tests carried out to cover all typical floors to establish the fire effect on the concrete strength for structural members particularly the columns since it is the most affected by reduction of concrete strength, the number of core samples are distributed on the floors as follows:

From 1st to 5th floor	(16 Nos.)
6th floor	(88 Nos.)
7th floor	(39 Nos.)
8th floor	(6 Nos.)

It can be deduced that the compressive strength of the floors from 1st to 5th comply with ACI 318 requirements while for other floors which are most affected by fire as follows:

- 6th floor 63% of core samples failed.

- 7th floor 84 % of core samples failed.
- 8th floor 90% of core samples failed.

7.2.2 Tension tests on Reinforcing steel

Ribbed hot rolled steel of grade 60 was used in reinforcement. Tensile tests were carried out on axis samples of Reinforcing steel from various locations which were directly exposed to the fire. It can be deduced form the test results on Reinforcing steel at 6th floor that the fire did not cause degradation in steel tensile strength except one sample which had a yield stress of 353 MPa, it can be considered as an isolated example of internal steel rather than an effect of the fire.

7.3 Structural Elements Design Check

The structural design check carried out to check the safety of columns, slabs and beams of 6th floor roof based on core test results. It can be deduced from the study that the reduction in concrete strength due to fire didn't affect on safety of beams of 6th floor while study of columns shows a significant difference from one column to another, so columns were divided into categories according to the status of each one.

8. Remedial works strategies

8.1 Repair Procedure

All repairs were carried out in accordance with the ACI 546 standard and manufacturer recommendations, the following steps are the general requirements for surface repairs:

- Prepare necessary equipment and manpower.
- Mark out the area to the repaired.
- Cut back around the area to be repaired.
- Remove contaminated / defective concrete and expose rear face of steel.
- Expose fully the steel bars.
- Clean steel bars by sand blasting.
- Clean the substrate.
- Apply prime coat to steel bars.
- Soak with clean water preferably under pressure.
- Prime the substrate where necessary according to the repair material selected and leave to become tacky.

8.2 Repair methodology:

Repairing methodology was classified according to the damage level obtained from assessment of fire damage on concrete elements as follows:

8.2.1 Class 1: (Superficial repair)

This type of repair procedure is required for smoke damage where fine to medium cracks appeared in beams, slabs and columns at 6th floor and lower floors. The surface should be protected with a suitable material which can elastically bridge the minor cracks as well as acting as filling agent preventing entry of harmful agents. the following steps were followed:

- Clean the concrete surface.

- Remove damaged concrete by hammer and chisel.
- Apply hand / dry packing materials.
- Finish the surface with trowel/ wood flush etc

8.2.2 Class 2: (General repair)

This type of repair procedure was carried for all structural elements where spalling has occurred as a result of fire. also for all beams within the zone of fire or which were exposed to heat significantly for some beams at 6^{th} floor and southeast part to elevators core of 7^{th} floor zone 2. Single component non-shrinkage flowable construction grout was applied in this case to replace the defective concrete, the following steps were followed:

- Preparation of the face: remove damaged concrete, expose steel bars, clean, prime steel bars.
- Clean substrate, soak with water
- Prime the substrate with bonding agent
- Apply non-shrinkage flowable construction grout by hand with sufficient pressure
- Finish the surface with trowel/ wood flush etc
- Apply curing compound

8.2.3 Class 3: (Principal repair)

This type of repair procedure was carried for 6^{th} floor columns which have inadequate concrete section and Reinforcing steel according to the structural calculations, the repair procedure was carried out as following steps:

- The structure was propped before cutting back the concrete. The props were remained in place until completion of repair works.
- All concrete cover was removed and exposed fully the steel bars using hand tools, light pneumatic tools or by grit-blasting.
- The surface was prepared to be sound, clean and roughened by wire-brushing or grit-blasting to ensure that the surface is not carbonated or dusty, and steel bars were cleaned by sand blasting.
- The buckled reinforcement bars were cut out and replaced. Anchors (12mm@ 200mm) were fixed staggered along the column length using bonding agents with minimum embedded length in column then additional rebar (16mm@ 150mm) was provided through the perimeter of jacket, stirrups (10@20mm) to be provided to tie the additional rebar.
- The column jacket material is shrinkage controlled fluid micro concrete, because it is relatively easy to produce, place, finish and cure. the jacket thickness applied for all repaired columns was 100mm. The finished surface is regular and free from sudden change in section.

8.2.4 Class 4: (Major repair)

This type of repair procedure was carried for all structural elements where significant loss of strength was occurred, so demolition and recasting was required for the columns located at the southeast part of Zone (2) of 7^{th} floor while no demolition was required for the roof slab, the following steps to be followed:

- propping slabs and beams before demolition of columns using temporary supporting steel system which have a capability to carry the load of slab and beams safely. The supporting system should remain in place until reconstruction works are complete and columns gain the required strength.
- Chip the concrete using hand tools or light pneumatic tools keeping the Reinforcing steel in place.
- Clean steel bars by wire brush or otherwise prepared to remove all surface deposit and loose rust scale.
- Recast the columns using concrete of grade K400.

9. Analysis and results:

The assessment of fire damage for the building was carried out through visual inspection, Schmidt hammer and concrete core test, in addition to the Structural calculations check on the affected concrete members. The study includes the effect of fire on the concrete members under 28 days age and Classification of remedial works strategies according to the assessment of fire damage.
The results of the assessment are mentioned in the following items:

1. Much of the damaged concrete had been recently cast before the fire. Areas younger than 28 days were as follows:
   - 8^{th} floor columns / walls between 3 & 10 days
   - 7^{th} floor roof – Zone 1 8 days
   - 7^{th} floor roof – Zone 2 12 days
2. Visible spall damage was generally localized at the columns / walls of 8^{th} floor and 7^{th} floor roof for Zone 1 and Zone 2 where formwork was still present at the time of fire, smoke damage was also noticed on lower floors.
3. Concrete and Reinforcing steel for columns/walls of 8^{th} floor was removed since it was recently cast (3 – 10 days old) and suffered from spall damage due to fire effect. In addition, core tests for column shows significant reduction in strength.
4. Concrete and Reinforcing steel for columns/walls and slabs of 7^{th} floor was removed (except Columns, walls, cores located at southeast part of elevators core of 7^{th} floor zone 2) since it was recently cast (8 – 19 days old) and suffered from severe damage while core tests for columns shows excessive strength reduction.
5. Columns, walls and cores located at southeast part of elevators core of 7^{th} floor zone 2 were repaired as per repair procedure (Class 4) described in this study since it was recently cast (19 days old) and generally suffered from spall damage. in addition, core tests for this members shows significant reduction in compressive strength.
6. Structural design check for slabs / beams of 6^{th} floor roof indicates safe condition for these members. Few of these elements were repaired as per repair procedure (Class 1 & Class 2).
7. Columns / Walls of the 6^{th} Floor were repaired as per repair procedure (Class 3) described in this report, according to Structural Design Check using reduced concrete strength based on concrete core results since test results showing significant loss in concrete strength varies from one place to another.
8. The fire did not cause significant reduction in tensile strength of reinforcing steel at 6^{th} floor since it did not extend beyond concrete cover depth.

9. The quality of construction below 6^{th} floor appears to be in a good condition, also core tests results for this floor comply with ACI 318 requirements, while slight smoke damage was repaired as per repair procedure (Class 1).

10. Conclusions and recommendations:

Based on the study analysis and results mentioned above, the following conclusions and recommendations are made:

10.1 Conclusions:

1. It can be concluded generally that concrete members younger than 28 days at the date of fire were suffered from severe damage so it should be removed.
2. Fire temperatures less than 300º C do not render concrete unusable because the temperature effect may be at only a small depth below the heated face, while concrete exposed to higher temperature suffered from significant loss of strength.
3. It’s clear from the study results that there is a minor effect of fire on the safety of the slabs and beams (except part of slabs supported by formwork and subjected directly to fire which subjected to severe damage and exposed steel in two layers), since slabs and beams were subjected to tension during the fire in the initial stages, which is mainly carried by their tensile reinforcement.
4. It can be concluded that the compressive stresses of slabs and beams are relatively low so that small losses of compressive strength didn’t affect their safety.
5. It’s obvious that the presence of Concrete formwork helps fire to spread and temperature to increase causing severe damage to concrete elements.
6. Columns were the most affected members by fire due to excessive loss of concrete compression strength and buckling of heated columns so the performance of columns has a significant impact on safety of reinforced concrete buildings in fire.
7. It can be deduced form the test results that the fire didn’t cause losses in steel tensile strength since the concrete at depth of cover subjected temperature lower than 600^{o}c, while Reinforcing steel subjected to more temperature was suffered permanent loss.
8. It can be concluded that most of fire damaged concrete structures are repairable Under most conditions.
9. Schmidt hammer test results provides high concrete strength value if it is compared with the core test results for the same structural members, so only compression tests on cores must be considered in the design check.
10. Accurate concrete repair strategies depend on assessment of fire damage and following of standard specification ACI 546 and manufacturer recommendations.

10.2 Recommendations:

1. It’s recommended to design beams and slabs considering low compressive stresses under ultimate value stated in design code to minimize impact of compressive strength losses due to fire damage.
2. All requirements of design code concerning durability and fire resistance must be followed considering thickness of concrete cover according to the required exposure class and fire rate.
3. It’s recommended to use the methodology of testing the fire damaged concrete to directly assess the concrete quality rather than using the methodology of

estimating the fire severity to assess the residual concrete strength, since the first methodology can express practically the actual strength of damaged concrete more than the second one, in addition to simplicity of the first methodology.

4. The quality assurance should be planned prior to start of any repair works. It can be practiced with specific attention to following items:

- Selection of repair materials according to previous performance records or manufactures or else by testing the repair material.
- Selection of experienced contractors in repair work.
- Quality control and inspection during execution of repair work.
- Evaluation after repair.
- Following standard specification requirements and manufacturer recommendations.

5. Accurate assessment of fire damage must be carried out through testing techniques in the site and laboratory and structural calculations check, the actual damage effect can be determined, so that accurate, cost-effective repair methodology can be developed.
6. The assessment of fire damage should include all structure elements, even the elements which have minor visible fire damage.
7. More researches are required to be achieved to compare between different methodologies of fire damage assessment, in addition to determine methods of increasing the efficiency of concrete against fire.

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