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Reliability of Nondestructive Tests on Damage Assessment of Mosul Museum Building after Liberation Events

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ABSTRACT

Nondestructive tests 'NDT' are increasingly becoming necessary tasks to develop accurate measurements without causing any damage to the tested elements. The outcome of the NDT is vital to determining the safety and reliability composition of materials. This study aims to investigate the dependability of nondestructive tests using Schmidt Hammer and Destructive Core Tests in a fire-damaged area. More than hundred stations were considered in the nondestructive inspection. Destructive core test results were used to assess the NDT results in burned concrete elements. The results of the comparison, clearly demonstrated the ability of both destructive and nondestructive ways to capture the strength reductions in fired elements. The NDT test provided an optimistic and higher strength prediction (higher 35-67%) as compared to destructive tests. Greater optimism NDT results were significantly associated with elements that have been highly damaged by fire and the strength predictions efficiency were between 60-67%. The results showed deviations in the mechanical properties of predicted burned concrete strength, by both on-destructive and nondestructive ways that required strength calibration to the nondestructive test to ensure more reliable assessment. A strength degradation formula is also suggested and is under review.

Keywords:

Reliability, Nondestructive tests,Core tests,Calibration.

1. INTRODUCTION

The results of 'NDT' can be vital to avoiding demolition which costs money and time [1]. Nevertheless, nondestructive testing is also used in the routine inspection schemes, to follow up the damage state in periodic checks and finally develop a proper rehabilitation methodology if required.

Many methods are used for performing NDT inspections by physical means, i.e. Schmidt hammer, Ultrasonic, Radiography, Eddy Current, Acoustic Emission, etc. [2; 3]. Unlike some other chemical methods, such as measuring the depth of carbonation with phenolphthalein indicator, sulfate and chlorate concentrations [4,5]. Each method was designed to spot defects in the material in different ways without permanently changing or causing additional damage to the elements. Among this range of NDT tests, the most common NDT methods are the Schmidt/rebound hammer, Ultrasonic and depth of carbonation tests, which are used to evaluate the surface hardness of concrete, concrete core quality, and corrosion in rebar respectively. However, the reliability of these various techniques requires further and deeper investigations corresponding to the structural conditions and/or damage levels. Many inspectors used NDT investigations to collect data and evaluate the health condition of systems and/or structures, i.e. assessment of seismic vulnerability of the National Museum of "Magna Grecia" structure.

The study indicated variation of the mechanical properties of the in-situ concrete using NDT and core strength of cylindrical specimens (cores) which were extracted from the same structural elements [6]. Therefore, the study adopted methods of analysis defined as Partial Safety Factors. Nondestructive tests (ultrasonic and rebound hammer) are used by Maio et al. [7] for evaluating damage to concrete strength exposure to high temperatures (150°C to 700°C). They also studied the effect of the exposed period and the cooling rate on the strength and static modulus of elasticity of damaged concrete.

The study concluded that sonic pulse velocity is a good tool for estimating the strength condition of burned concrete samples. The ultrasonic method is used for mapping the degree of degradation of concrete exposed to high temperature [8, 9]. Chew [10] analyzed the effect of elevated temperatures on the compressive strength of concrete incorporating factors such as W/C ratio and time of exposures. The study concluded that water-cement ratio is not a sensitive factor like exposure to heat and the concrete mixture. The strength degradation in both heating and cooling phases was studied by Li and Franssen [11]. The study compared the experimental results and proposed formula with the residual compressive strength of concrete after a fire with the Eurocode 2.

NDT inspection approach also can be a good option to explore the structural damage of historical remains and helps to examine the defects/status in different ways [12-15].

In short, nondestructive investigation techniques are sensitive to thermal characteristics of materials that are related with the physical, mechanical properties of materials or physicomechanical. Such changes cannot be captured precisely without heat calibration factor. Therefore, this study discusses the reliability of nondestructive tests in badly damaged areas by fire. Both destructive (core) and nondestructive (hammer) tests are utilized to describe the post damage status. A heat calibration formula 'ϕ' that accounts the concrete strength degradations due to heat effects in the NDT test measurements is proposed.

2. RESEARCH SIGNIFICANCE

The assessment of the structure elements post-damage with NDT can be broadly defined as the ability of an element (with the current status) of building to fulfill its designed function for a period of time [16]. The residual condition of structures post-damage is mainly concerned with the strength and serviceability performance in the long-term health of the structure. Proper assessment of the loss of a structure elements or its strength after the damage event plays a vital role in rehabilitation and maintenance process. This study focuses on the topic of the residual condition of structure elements after damage and on testing the reliability of the NDT test, as this is more pertinent for a post-damage evaluation issue and the needs for calibrating the nondestructive test results with heat factor.

3. MOSUL MUSEUM PRIOR DAMAGE

Mosul Museum was the second largest museum in Iraq after the National Museum of Iraq in Baghdad. The construction had started in 1969, and the building was opened in 1972. The super structure RC frame was constructed on an area of 1,620 m2. Figure 1 shows Mosul Museum in early 1972.
Figure 2 shows the plan view of the Museum. The basement consists of north entrance, conference hall, library, staff offices, art storage and lab. The ground floor is divided in to three main divisions, in addition to the reception lobby. The Mezzanine level is marked by the dash line at the core of the museum, designed to provide a better view for the visitors to look at all main halls from the top.

Fig. 1 Mosul Museum in 1972.

The museum roof is constructed mainly from precast concrete slab, with enough skylight facilities made of short glass block and 1.2m concrete brick walls on the top roof. The destruction of Mosul Museum artifacts became publicly known on February 26, 2015 when ISIS released a video showing their destruction. ISIS severely demolished the Assyrian hall by detonation of high explosives at the ground floor.

In 2018, preliminary damage assessment for Mosul Museum structure was done and reported by Yousif et al. [17]. In the current study, both destructive and non-destructive tests in badly damaged areas by fire were reiewed and discussed following the meeting requirements of BS 6089 [18] and ASTM E 119 [19].

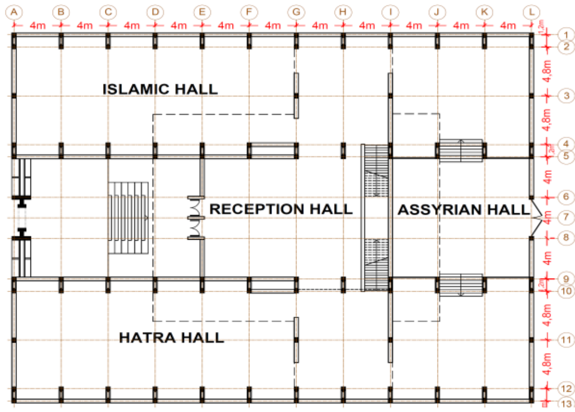

Fig. 2 Schematic diagram of Museum plan.

4. PRIMARY SOURCES OF DAMAGE DUE TO FIRE

Fire at the basement floor: The library was burnt during the liberation of Mosul, June 2017. Burning this library was part of the master plan of setting a large part of the city of Mosul on fire. The zone surrounded between grids 'F' to 'L' intersects with grids '1' to '5' (Figure 2) was severely burned out. The fire damaged the concrete cover for slab reinforcements, as shown in Figure 3. Some beams were severely affected by heat, and shear cracks were noted at several locations, as shown in Figure 4, (e.g. beams located along grid ‘I’ and between grids ‘2’ to ‘4’). To check the concrete status at the core of the beam, a small chip of concrete was gently removed, as illustrated in Figure 5 and it was noted that the concrete color has been changed due to the heat.

Fig. 3 Damaged concrete cover for slab reinforcements in the library hall.

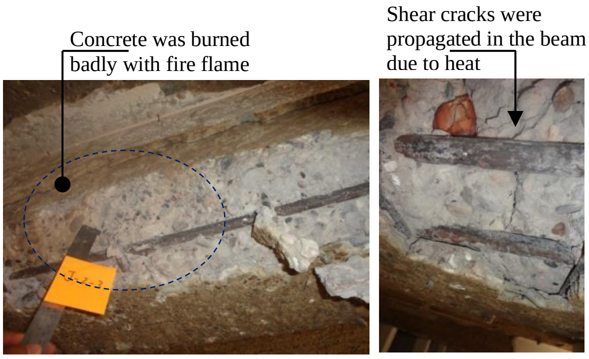

Fig. 4 Damaged beam in the floor of library hall.

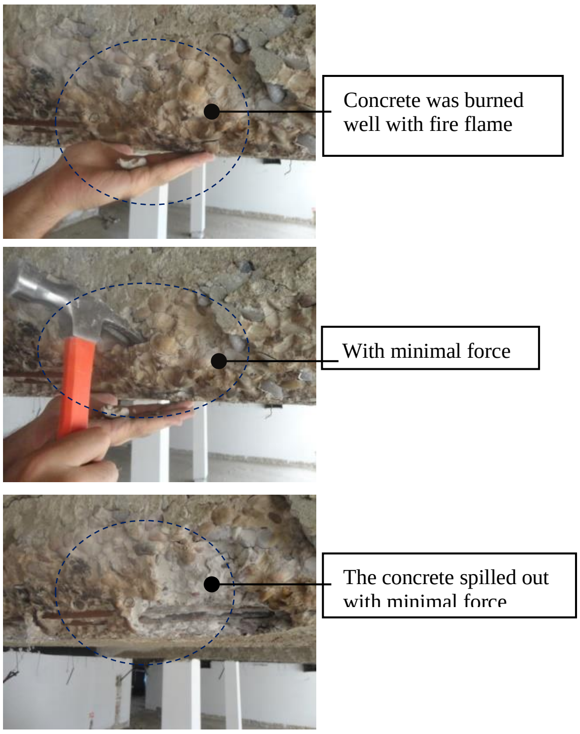

Fig. 5 Heat reached to the beam core in floor.

5. EXPERIMENTAL AND VALIDATION PROCEDURE

Schmidt Hammer Tests are used to assess concrete compressive strength. This test was performed on more than 100 different locations around the structure, footings, columns, beams, slabs etc. Before the test, each station is cleaned and the concrete face is smoothen with grinding machine and abrasive sandsheet, as illustrated in Figure 6. At each station, 16 sampling points were measured and tabulated. Then, the standard deviation was calculated, the deviations of individual sample readings showed minor deviations.

Fig. 6 Arrangements for hammer test at each station.

The whole non-destructive test was done satisfying BS 1881 Part 201 [20] and Part 202 [21] standards. Figure 7 shows the measured strength process for one sample station. Complete sets of measurements for all stations with the corresponding locations are provided in Figure 8. The strength reduction was significantly high at the library; some elements have strength less than 10 MPa, (i.e. station ST5, 17, 14 and 21, highlighted with red color).

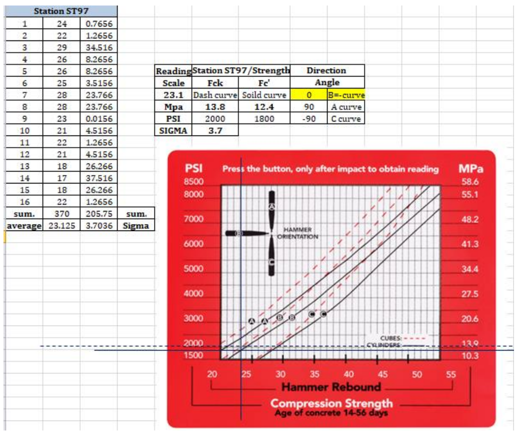

Fig. 7 Estimating strength capacity using hammer test.

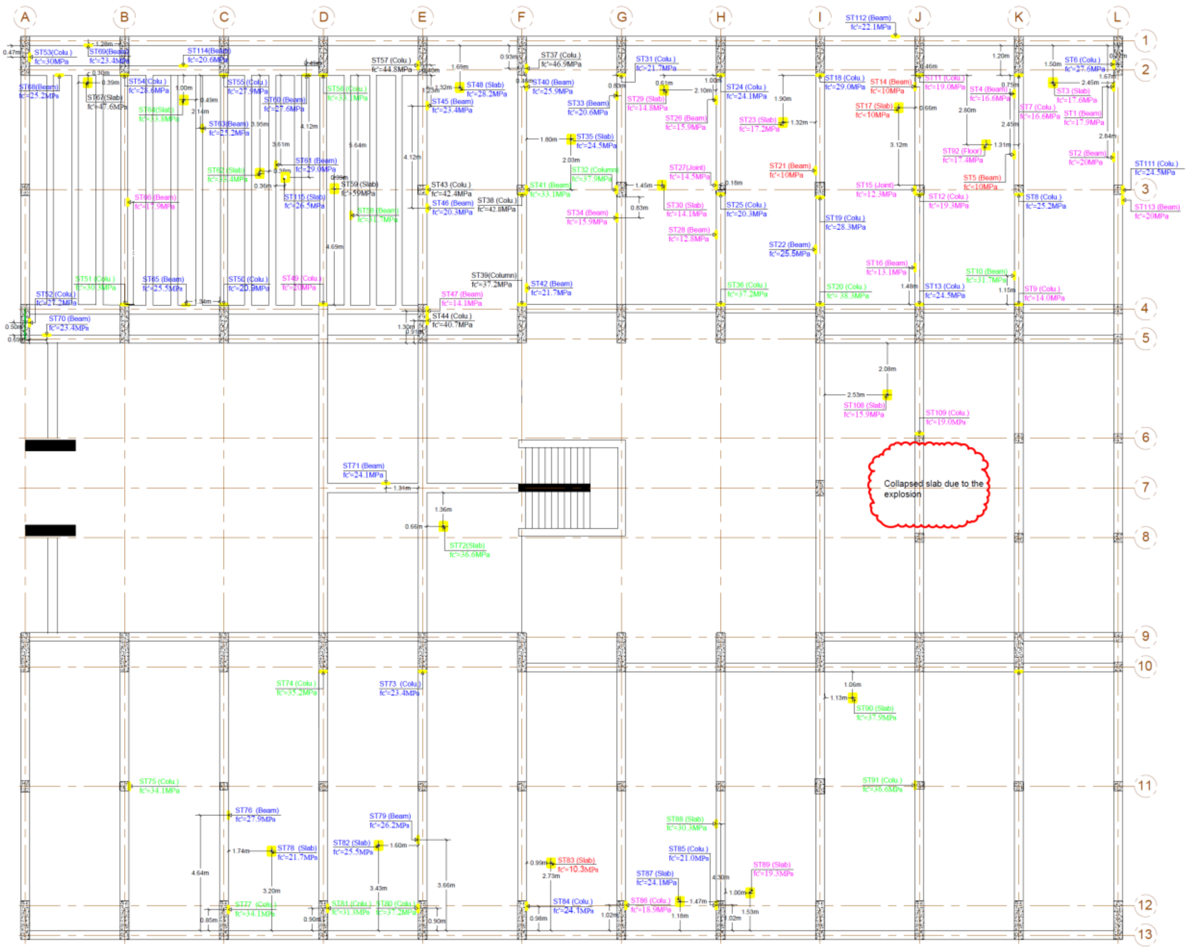

Fig. 8 Schematic diagram for the NDT.

Nevertheless, the rest of stations at the library showed low strength measurements (10 to 20MPa) and are highlighted with magenta color. Unlikely, the blue, green and black colors are used to descript the strength measurements at a range of 21 to 30MPa, 31 to 40MPa and 41 to 50MPa respectively. In the current practice, the reliability of non-destructive test results for structural elements affected severely by fire is examined by considering destructive core test for the areas that were highly damaged by fire (library), as illustrated in Figure 9. Cores A, D and G are collected from basement slab (100mm core diameter penetrated the slab thickness, 150mm).

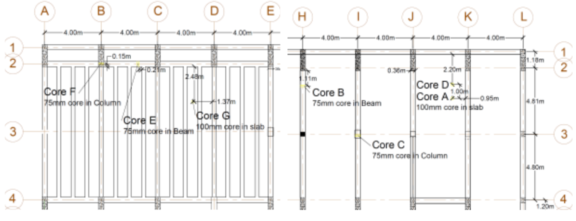

Fig. 9 Schematic diagram of locations for the cores.

Core B, E and C, F were 75mm diameter cores collected from basement beam and column, respectively. Figure 10 shows the sampling of B and D cores. All the destructive core samples were done, satisfying ACI 214.4R [22] code requirements.

a) Core B at beam b) Core D at slab

Fig. 10 Cores sampling.

Lab results show that the density of the concrete is classified as normal concrete density for all tested samples and that the severe heat did not show any notable impact on the concrete density. The strength of the destructive core samples at the library shows significant reduction in its strength, as illustrated in cores results in D and B samples for slab and beam (fc less than 10MPa).

Table 1 Destructive test results.

Element	Core	Mechanical Characteristics					Failure shape
		Dimensions (mm)	Volume $(m^3)\times10^{-3}$	Density (kg/m^3)	Strength (MPa)	Sampling orientation	
Slab (Library)	**A***	Ø93.8×70	0.484	2270	**10.9**	Vertivatical Angle=90^O	
Slab (Library)	**D**	Ø93.3×106.5	0.728	2320	**11.03**	Vertivatical Angle=90^O	
Beam (Library)	**B**	Ø68.4×109.2	0.403	2300	**9.50**	Horizantal Angle=0^O	
Column (Library)	**C**	Ø68×126	0.458	2350	**20.9**	Horizantal Angle=0^O	
Beam (Hall)	**E**	Ø68×130.1	0.473	2440	**13.8**	Horizantal Angle=0^O	
Column (Hall)	**F**	Ø67.7×134.7	0.485	2415	**21.2**	Horizantal Angle=0^O	
Slab (Hall)	**G**	Ø93.3×106.5	0.728	2320	**18.2**	Vertivatical Angle=90^O	

* The dimensions of sample A was substandard as per ACI 214.4R-10 [22], Therefore, sample D was considered instead.

Table 2 compares destructive (core) and nondestructive (hammer) concrete test results for the strength of the residual condition of structure elements (slab, beam and column) at the library for the same elements after damage, and this was performed to test the reliability of the NDT strength test in various elements post-damage by fire.

Unlike core sample C of the column in the library showed decent strength capacity (fc is nearly 21MPa). It seems that the column core (the confined concrete in between ties) appears to be in a decent condition and less affected by the heat.

Table 1 summarizes the destructive core designations and testing results. In addition to this, the failure types have also been recorded. Both Core D and C have pure compression failure mode, unlikely shear failure mode is noted at Core B. Since the slab and beam were severely affected by fire, the strength of these elements dropped significantly. And by considering nondestructive core test as more reliable test results, NDT strength results were much more optimistic results and were provided higher strength predictions (58 and 67%, higher in slab and beam respectively). However, the variations were less in conference hall due its considerably less damage by fire.

Table 2 Comparison of destructive (core) and nondestructive (hammer) test results.

Element	Designation	Strength (MPa)	Strength ratio, NDT/Core
Slab (Library)	**ST92** **Core D**	17.4 11.03	**1.58**
Beam (Library)	**ST26** **Core B**	15.9 9.5	**1.67**
Column (Library)	**ST19** **Core C**	28.3 20.9	**1.35**
Beam (Library)	**ST114** **Core E**	20.6 13.8	**1.49**
Column (Library)	**ST54** **Core F**	28.6 21.2	**1.35**
Slab (Library)	**ST115** **Core G**	26.5 18.2	**1.46**

While the column that was moderately affected by fire (was not under direct flame) has considerably moderate strength residual, the NDT strength result were less deviations (NDT strength test result showed 35% higher than Core test). Generally, in assessing the structural strength condition post-damage by fire, NDT strength test results provided optimistic higher strength predictions than the destructive core test results for the same tested elements. The results of the current study clearly showed that non-destructive investigation techniques are sensitive to thermal characteristics of materials. Therefore, such changes require a heat calibration factor for strength degradation at various heat levels.

6. CALIBRTION HEAT FACTOR FOR NDT STRENGTH TEST

A statistical calibration heat factor for NDT strength test on a large number of NDT tests developed in the form of basic linear generic model was calibrated using Table 2 (destructive and nondestructive tests). Figure 11 shows the calibration of NDT test, depending on the strength degradation level by destructive core test.

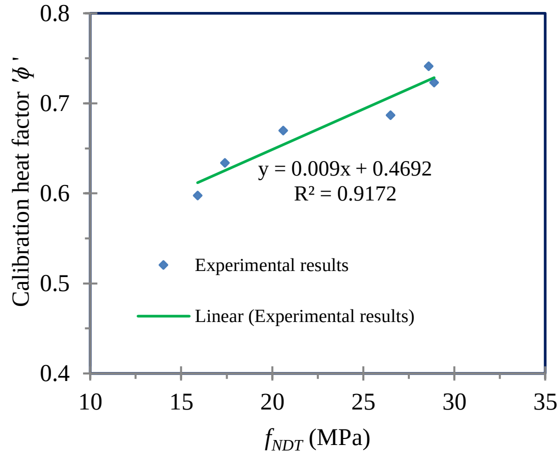

Fig. 11 Calibration factor for NDT strength test.

Eq.(1) accounts for the heat factor depending on the destructive core test. While, Eq.(2) gives strength degradation for NDT calibrated empirical from destructive tests.

$$\phi = 0.009 \times f_{NDT} + 0.47 \qquad \ldots\text{Eq.(1)}$$

$$fc = \phi \times f_{NDT} \qquad \ldots\text{Eq.(2)}$$

Where; ϕ is the heat calibration factor for NDT compressive strength degradation, fNDT is the un-calibrated strength measured by NDT test. fc calibrated strength for burned concrete elements. Table 3 shows the calibrated non-destructive (hammer) test results for the tested data (selected samples for the range tested data). The empirical Eq.(1) with a low root mean square error (R^2=0.92) means that the calibrated strength values are close to the real values.

Figure 12 displays the complete calibrated strength of the burned concrete at the basement level of the museum. A significant difference between calibrated strength with the predicted NDT test results (un-calibrated NDT strength results displayed in Figure 8) is noticed. The heat calibration factor evaluates for strength degradation at various heat levels. It almost exactly matches the distractive core test in stations ST19, ST26 and ST92 (Table 3). By comparing both calibrated and un-calibrated NDT results in Figures 16 and 20, the adopted assessment can be quite different and it deviates significantly when the heat factor is considered.

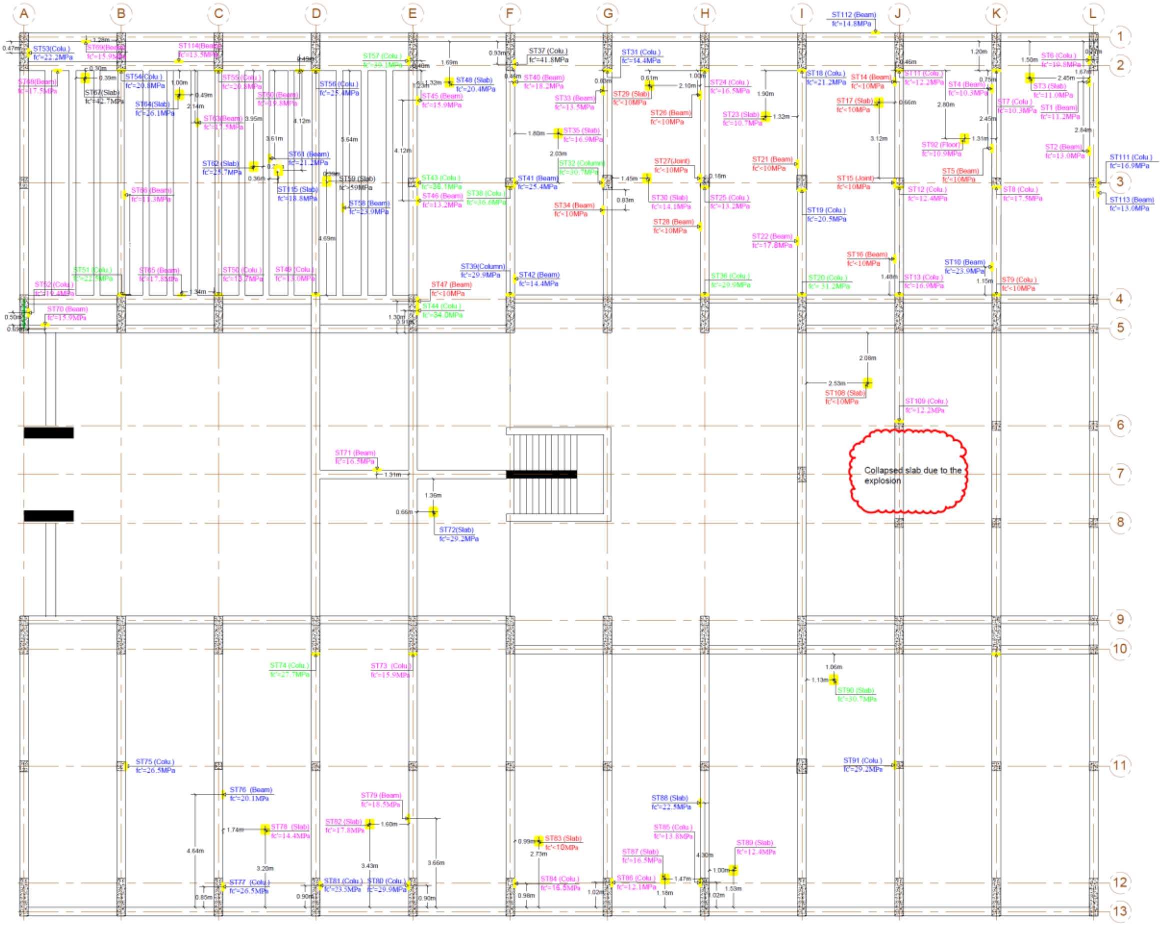

Fig. 12 Calibrated NDT strength results in the burnedconcrete at the basement.

Table 3 Calibrated nondestructive (hammer) test results (selected samples for the range tested data).

Designation	Strength, f_{NDT} (MPa)	Heat calibration factor, ϕ	Calibrated, f_c (MPa)
ST10	31.7	0.75	23.9
ST19*C	**28.3**	**0.72**	**20.5**
ST20	38.3	0.81	31.2
ST26*B	**15.9**	**0.61**	**9.7**
ST30	14.1	0.60	8.4
ST40	25.9	0.70	18.2
ST50	20.9	0.66	13.7
ST54*F	**28.6**	**0.73**	**20.8**
ST60	27.6	0.72	19.8
ST70	23.4	0.68	15.9
ST80	37.2	0.80	29.9
ST90	37.9	0.81	30.7
ST92*D	**17.4**	**0.63**	**10.9**
ST100	25.5	0.70	17.8
ST110	15.2	0.61	9.2
ST114*E	**20.6**	**0.65**	**13.5**
ST115*G	**26.5**	**0.71**	**18.8**

*C The distractive core-C strength test was 20.9MPa
*B The distractive core-B strength test was 9.5MPa
*F The distractive core-F strength test was 21.2MPa
*D The distractive core-D strength test was 11.03MPa
*E The distractive core-E strength test was 13.8MPa
*G The distractive core-G strength test was 18.2MPa

7. CONCLUSION

Non-destructive testing is considered an effective way in the basic strength prediction approach in the structure residual condition post-damage evaluation. However, the reliability of the NDT on damage assessment of the residual condition of structures post-fire was examined during the inspection of a real case assessment of the Mosul Museum building. The current study has come up with the following conclusions:

i) Both destructive and non-destructive tests proved their ability to examine the structure residual condition post-damage by fire, with poor and incompatible (overestimation) predictions in the latter.

ii) The NDT provided an optimistic and higher strength capacity than the accurate and reliable destructive test measurements. Corresponding to highly damaged elements by fire, NDT provided higher strength predictions (60% more than the destructive core test). The element that was moderately affected by fire has considerably less deviation, though (NDT strength test result showed 35% higher than destructive core test). The outcomes of the current practice showed that considering only NDT (hammer test) for highly fired RC elements can negatively influence the damage assessment and perceiving risks. However, inaccurate evaluation can have a significant impact on the simulation and, as a result, on the quality of the rehabilitation methodology.

iii) The results showed deviations of the mechanical properties of burned concrete, by both on-destructive and non-destructive ways. So, the study emphasizes the need to calibrate the strength performance in nondestructive techniques with the strength of core destructive test that were extracted from the same burned structural elements to ensure more reliable assessment. The study proposes heat calibration formula ‘ϕ’ for accounting precisely the concrete strength degradations, that accounts for heat effects on NDT measurements.

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موثوقية الاختبارات غير الاتلافية فى تقييم الاضرار لمبنى متحف الموصل بعد احداث التحرير

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الملخص

ان زيادة الاهتمام على الفحوصات غير الائتلافية يتطلب تطويرها ومعايرة قاسيتها دون التسبب في اي اضار اضافية للعناصر المفحوصة. تعتبر نتيجة الاختبار غير التدميري أمرًا حيويًا لتحديد مكونات السلامة والموثوقية للمواد. ان الهدف من الدراسة الحالية هو فحص موثوقية الاختبارات غير التدميرية باستخدام المطرقة مع الاختبارات المدمرة في اماكن شديدة التلف بسبب الحريق. في الدراسة العملية، تم اعتماد في أكثر من مائة محطة في عملية التفتيش غير الائتلافي. تم استخدام الاختبارات الأساسية المدمرة ايضا لتقييم نتائج الاختبارات غير التدميرية في العناصر الخرسانية المحترقة. أظهرت نتائج الدراسة الحالية بوضوح قدرة الفحوصات المدمرة وغير المدمرة لالتقاط انخفاضات القوة في العناصر المحروقة. وأظهره الاختبارات الائتلافية تنبؤًا متفائلًا وقوة أعلى (أعلى من 35-67٪) مقارنة بالاختبارات المدمرة. كانت نتائج الفحوصات غير الائتلافية منحرفة وأعطى تفاؤلا أكبر وخصوصا في العناصر التي تضررت بشدة بسبب الحريق وكانت كفاءة التنبؤات بين 60-67٪ فيها. شخصت الدراسة الحالية و جود انحرافات في الخصائص الميكانيكية لمقاومة الخرسانة المحترقة المتوقعة في كل من فحص المطرقة غير المدمرة بالمقارنة مع الفحوصات المدمرة (فحص الاختراق) ولذلك يستوجب معايرة لنتائج الاختبارات غير المدمرة لضمان تقييم أكثر موثوقي. كما تم اقتراح معادلة معايرة لتدهور القوة باعتماد على الفحوصات التدمرية.

الكلمات الداله :

الفحوصات غير التدميرية ، *الموثوقية، فحص الاختراق، المعايرة.*