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Fast Assessment of Post-Fire Residual Strength of Reinforced Concrete Frame Buildings Based on Non-Destructive Tests †

Pablo Alcaíno [1,2,*], Hernán Santa María [1], Michael Cortés [2] and Jennyfer Alfaro [3]

[1] Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Santiago 7820436, Chile; hsm@ing.uc.cl
[2] I3Pro SpA, Santiago 7591313, Chile; mcortesb@outlook.com
[3] School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso 2362804, Chile; jennyfer.a.a.f@gmail.com
* Correspondence: palcaino@uc.cl
† Presented at the 18th International Conference on Experimental Mechanics (ICEM18), Brussels, Belgium, 1–5 July 2018.

Published: 27 June 2018

Abstract: Assessment of the residual strength of reinforced concrete buildings subjected to fire is a problem that many times requires a very fast resolution that is necessary for the action of firemen and/or for forensic fire investigation and/or structural assessment of post-fire condition of the building: in all cases safety and integrity of firemen and researchers can be at risk, and it is necessary to have quick and sufficiently reliable information in order to choose whether enter freely, enter with caution or simply do not enter the burned structure, so there is no time or background to develop mathematical models of damage propagation and/or of the structure. This work presents an experimental methodology for a fast assessment of post-fire residual strength of reinforced concrete frame buildings based on the high correlation between the loss of strength and non-destructive tests results of frame concrete elements subject to fire action.

Keywords: post-fire residual strength; non-destructive tests; reinforced concrete building

1. Introduction

Assessment of the residual strength of reinforced concrete buildings subjected to fire is a problem that many times requires a very fast resolution that is necessary for the action of firemen and/or for forensic fire investigation and/or structural assessment of post-fire condition of the building. In all cases safety and integrity of firemen and researchers can be at risk [1], and it is necessary to have quick and sufficiently reliable information in order to choose whether enter freely, enter with caution or simply do not enter the burned structure, so there is no time or background to develop mathematical models of damage propagation and/or of the structure, nor is there time to extract specimens of materials and test them in the laboratory in order to diagnose the state of the structure under analysis, even in an approximate way. Additionally, it will be necessary to choose the future of the building: repair or demolish. Considering the high costs of replacing the burned nonstructural elements, equipment and the high cost of sophisticated studies to determine the level of loss of strength the structure, to have a simple and fast methodology based on quick and low-cost testing is very convenient.

A lot of research report forensic assessment of cases of study considering destructive and non-destructive material's testing [2–7], and advanced mathematical-computational models, but their results have not been completely generalized [8–11] and only some of them consider the applicability of the results to real situations. Then, the objective of this paper is to present an experimental methodology for a fast assessment of post-fire residual strength of reinforced concrete frame buildings based on non-destructive testing.

2. Materials and Methods

Eighteen reinforce concrete columns and beams have been designed and constructed according to the current design codes [12–14] to obtain structural elements representative of a building reality. The concrete mixture used is shown in Table 1 to obtain a nominal cylindrical compression strength of 20 MPa (reliability 90%). Steel reinforce bars used has a nominal yield stress of 280 MPa and tensile strength of 440 MPa. The dimensions of specimens, amount and diameter of steel bars used are shown in Table 2.

Table 1. Proportions of concrete mixture used [1].

Material	Cement	Sand	Gravel	Water
% (kg/m^3)	18.2 (436)	36.4 (873)	36.4 (873)	9.1 (218)

Table 2. Dimensions and reinforce bars of specimens [1].

Specimen	Length (mm)	Width (mm)	Height (mm)	Upper Bars	Lower Bars	Stirrups
Columns	600	200	250	2φ8 mm	2φ8 mm	φ8@50 mm
Beams	650	150	250	2φ6 mm	2φ8 mm	φ8@100 mm

Each type of specimen has been grouped into six identical sets of three elements and they are subjected to the non-destructive tests (NDT): Esclerometric index (EI) using a standard Schmidt test hammer and a standard procedure [15]; and Ultrasonic pulse velocity using a Pundit Lab® equipment considering three use modes [16-17]: (a) direct (UPV-D), with the pulse emitter and pulse receiver located on opposite faces of the specimen; (b) indirect (UPV-I), with the pulse emitter and pulse receiver located on the same face of the specimen; and semidirect (UPV-S), with the pulse emitter and pulse receiver located on adjacent faces of the specimen. These tests were performed before and after the burning test, which had a duration of 0 (reference set), 30, 60, 90, 120 and 180 min according to the tested set [18,19]. An electric oven (Figure 1a) with controlled temperature between 700 and 1000 °C was used to model the fire according to the literature and current standard codes [18,19] (Figure 1b). The columns were subjected to the action of fire on the entire lateral surface (columns' four sides); instead, the beams were only exposed to fire directly on three of its four faces (its upper face was always protected by a concrete slab, Figure 1c). More details of fire test setup in [1].

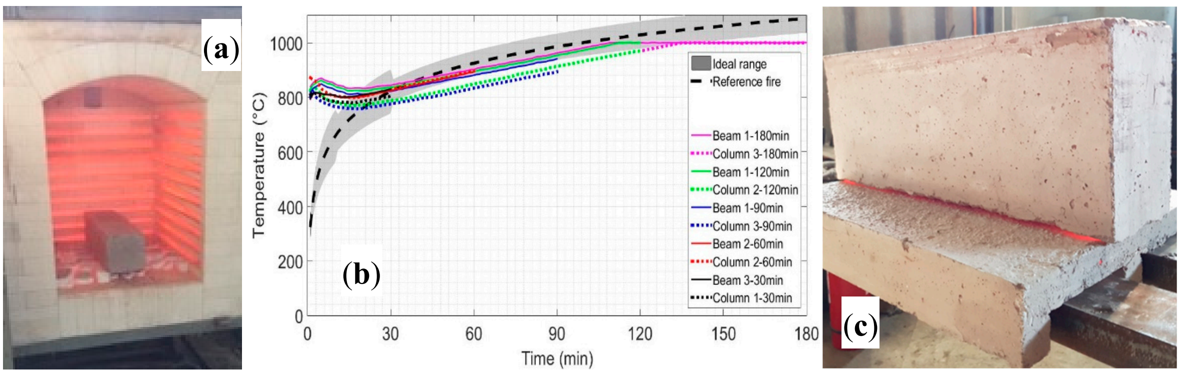

Figure 1. Burning experimental setup: (**a**) Used electric oven; (**b**) Standard fire curve and some testing temperature curve (examples); (**c**) Burning setup of beams.

After the specimens cooled down to room temperature, each of them was subjected to destructive strength tests: columns were subjected to simple compression [20], while beams were subjected to four points bending test with loads concentrated on the thirds of the distance between supports [1,21] considering an approximately bending velocity of 1 mm/s. In all cases, the applied load, the deformation and the failure modes were recorded and analyzed.

3. Results and Discussion

The failure modes in compression (columns) are characterized by greater and faster loss and crumbling of the unconfined concrete as the time of exposure to fire increases (see Figure 2a). In the beams, the failure mode is characterized by decrease of both shear and compression strength near the supports, mainly due to the loss of anchorage and effectiveness of the shear reinforcement due to the concrete strength loss (see Figure 2b,c). This failure is more significant as the time of exposure of fire increases.

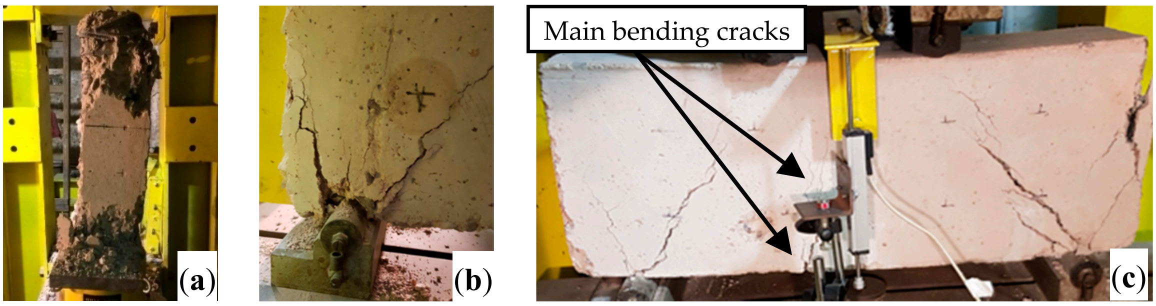

Figure 2. Observed failure modes: (**a**) Compression failure of burned reinforce concrete column: loss and crumbling of concrete cover, while the confined concrete core remains relatively undamaged; (**b**) Shear-bending failure of burned concrete beam: the shear and bearing failure at the supports become more significant as the fire time increases. (**c**) Main bending cracks at the center of the beam are less important in beams with longer burning time.

A decrease of strength in columns and beams with increase of time of fire exposure is recorded. A high correlation between the loss of strength and the time of exposure to fire has been obtained. The residual strength is defined as R/R_0, the ratio between the strength of each specimen (R) and the average strength of the unburned specimen set (R_0).

In the same way, the variation of NDT results is defined as the ratio between the NDT parameter of each specimen (EI, UPV_D, UPV_I, UPV_S) and the average parameter NDT for the unburned specimen set (EI_0, UPV_D_0, UPV_I_0, UPV_S_0). It was observed a high correlation between these variations and the time of exposure to the fire action. Therefore, it is reasonable to define the correlation between the variation of the results of both NDT and the loss of strength, which are shown in Figures 2 and 3 for the columns and beams, respectively. The EI and the UPV-D are the NDT parameters that produce the best estimates of the residual strength of column strength: Figure 3a,b show the best fit logarithmic functions (correlation functions) and that the determination coefficients R^2 are greater 0.8. On the other hand, the UPV-S and the UPV-I are good predictors of the residual strength ratio only for the beams (see Figure 3c,d and Figure 4c,d).

Considering a well-known failure criterion based on residual strength for compression [22] and for shear-bending [23] elements, and the normalized relationship between the results of NDT and residual strength, it is possible to present an experimental procedure to quickly and roughly assess the condition of the burned structure. This methodology is as follows: first, to measure the NDT's parameter in areas of reinforced concrete elements burned and not affected by fire and obtain a ratio of NDT parameter used. Then, considering the type of frame element (column or beam) and the NDT parameter ratio selected, use the correlation functions proposed to estimate the strength ratio of the element. Finally, according to the safety criterion proposed in [22,23], if the resistance ratio is over 0.80, the element under study have a very low collapse probability, if the strength ratio is between 0.80 and 0.60 the collapse probability is moderate, and it is under 0.60 the collapse probability can be considered high.

In Table 3 are shown the NDT parameter ratios calculated from the correlation functions for the ranges of strength ratios considered.

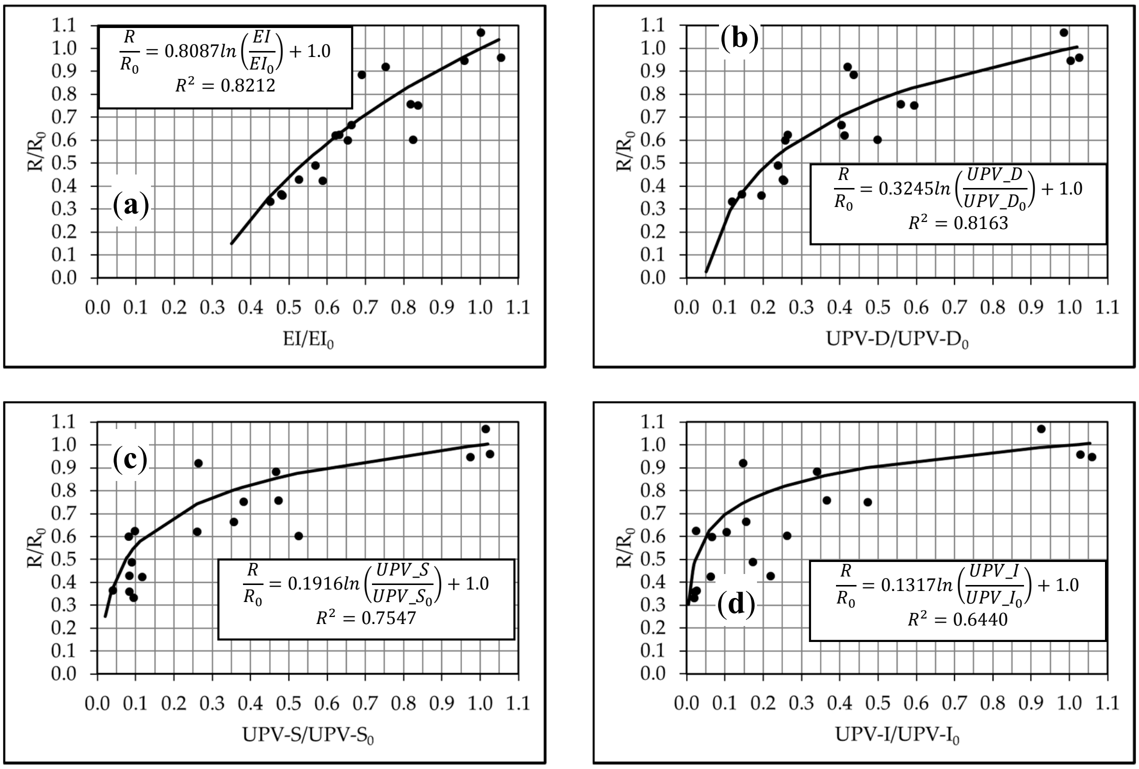

Figure 3. NDT ratio versus strength ratio and correlation function in columns according to: (**a**) EI; (**b**) UPV–Direct; (**c**) UPV–Semidirect and (**d**) UPV–Indirect.

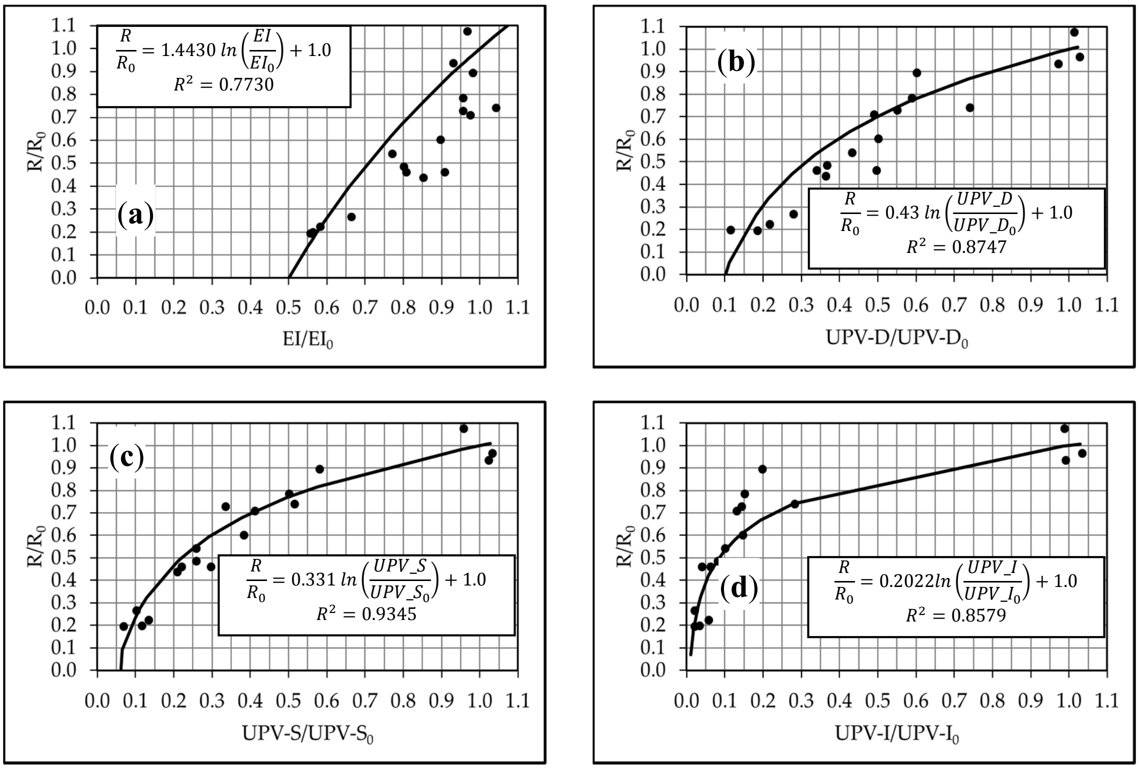

Figure 4. NDT ratio versus strength ratio and correlation function in beams according to: (**a**) EI; (**b**) UPV–Direct; (**c**) UPV–Semidirect and (**d**) UPV–Indirect.

Table 3. Limits of NDT ratios according with safety criterion based on strength ratio.

	Columns				Beams			
R/R_0	>0.80	<0.80	>0.60	<0.60	>0.80	<0.80	>0.60	<0.60
	Safety	Caution		Danger	Safety	Caution		Danger
EI/EI_0	>0.78	<0.78	>0.61	<0.61	>0.87	<0.87	>0.76	<0.76
UPV_D/UPV_D_0	>0.54	<0.54	>0.29	<0.29	>0.63	<0.63	>0.39	<0.39
UPV_S/UPV_S_0	>0.35	<0.35	>0.12	<0.12	>0.55	<0.55	>0.30	<0.30
UPV_I/UPV_I_0	>0.22	<0.22	>0.05	<0.05	>0.30	<0.37	>0.14	<0.14

An intuitive color code has been used in Table 3 to facilitate the use and interpretation of the method. It is possible see that the use of this methodology to the fast assessment of post-fire residual strength of reinforced concrete frame buildings based on non-destructive tests is easy, quick and cheap.

4. Conclusions

An extensive experimental program has been developed including the design and construction of eighteen reinforced concrete columns and beams. Fifteen of these eighteen columns and beams were subjected to a simulated fire in laboratory during controlled time. All specimens were subjected to NDT (EI and UPV) before and after burning test. Finally, strength tests were made for each specimen. The correlation between the variation of the NDT results (or NDT parameter ratios) and the residual strength (or strength ratio) for different time of fire exposition was analyzed and empirical correlation functions with high determination coefficient (R^2) were proposed. Using this correlation functions an easy and cheap methodology for the fast assessment of post-fire residual strength of reinforced concrete frame buildings is presented. This methodology, which need only one or two instruments for NDT, quick and easy measures and a little calculus, enables the definition of, for example, work' safety conditions of firemen, forensic researchers, and define the future actions over the burned reinforced concrete building.

Author Contributions: This work is the partial result of the doctoral research of the first author, P.A. at the Pontificia Universidad Católica de Chile. He is the designer of the research, tests, methodology of analysis and main writer of this document. The second author, H.S.M. was the supervisor of this research, which had reviewed the methodology, the results and the present text. The two last authors, M.C. and J.A., supervised the execution of the tests and contributed to the data analysis.

Acknowledgments: Financial support for the construction and testing of specimens was provided by Bomberos de Chile. The equipment for the fire, non-destructive and destructive tests was provided by Pontificia Universidad Católica de Valparaíso. The scholarship for the doctoral research of the first author was provided by CONICYT, the national research council of Chile.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the study's design; in the collection, analyses, or interpretation of data; in the writing of the manuscript, nor in the decision to publish the results.

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