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Heuristic Machine Cognition to Predict Fire-induced Spalling and Fire Resistance of Concrete Structures

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Abstract

The exceptional behavior of concrete under fire conditions is often jeopardized by concrete’s propensity to spall. While published works seem to agree on the complexity and randomness of fire-induced concrete spalling, attempts carried out in the past few years continue to be short of developing a systematic methodology that enables accurate prediction of this phenomenon. Unlike previous works, this study aims at understanding fire-induced spalling of concrete through a modern perspective. In this study, Machine Cognition (MC), a branch of Machine Intelligence (MI), is used to derive expressions able of accurately tracing fire response of concrete structures. These expressions take into account geometric, material, and specific features/properties of reinforced concrete (RC) columns in order to predict occurrence and intensity of fire-induced spalling as well as to evaluate fire resistance of such structural members. The derived expressions implicitly account for high-temperature properties of concrete and steel, and thus do not require input of such properties nor special simulation environment. These expressions, arrived at through observations obtained from actual fire tests, have been calibrated and validated for fire exposures far exceeding that of four hours and their prediction capability was examined against commonly used calculation methods such as those adopted in European and Australian codes.

Keywords: Spalling; Fire resistance; Artificial intelligence; Concrete; Columns.

1.0 Introduction

Concrete is a naturally inert construction material and hence is suitable for use in extreme conditions such as those associated with high temperatures or rapid temperature changes (i.e. off-

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shore platforms, nuclear power plants) [1]. In fact, concrete, along with its derivatives, is perhaps one of the only construction materials that do not require to be fire-proofed for most structural fire applications; given that a RC member is designed with a proper cover to steel reinforcement. The superior behavior of concrete under elevated temperatures can be attributed to its low thermal conductivity, high specific heat capacity, and slow degradation of strength properties. While concrete, and similar to other construction materials, undergoes a number of physio-chemical changes once subjected to elevated temperatures, structural members made of concrete can still maintain their structural integrity for extended period of time and then promptly recover post exposure to fire trauma [2,3]. As a result, concrete has been extensively used in unique/demanding projects and those requiring higher levels of resilience [4,5].

Exposure to elevated temperatures may alter key characteristics of concrete through development of high pore pressure and thermal gradients; both of which often lead to spalling. Fire-induced spalling is generally defined as the explosive breakout of concrete chunks driven by fire [6]. In other words, spalling causes large reduction of concrete cover and overall cross-sectional area at the local or global scale in a RC member. This loss of cover, exposes steel reinforcement and internal concrete layers to fire, thereby accelerating rate of strength and modulus deterioration causing additional losses in axial bearing capacity [6]. The degradation in mechanical properties in concrete and steel reinforcement, combined with loss of concrete cross section due to spalling, considerably lower fire resistance of a RC structural member (i.e. column). Fire-induced spalling may also lead to premature loss of stability which can trigger dynamic and progressive collapse [7,8].

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Fire-induced spalling generally occurs in modern/advanced (eg. high strength/high performance) concretes as they naturally have lower permeability and water/cement ratio as compared to that in traditional concretes (i.e. normal strength concrete) [3,6]. The occurrence of spalling complicates fire resistance evaluation and as a result, predicting thermal and structural response of concrete structures (or structural members) becomes a challenging task [9,10]. While it is true that currently adopted fire codes and standards often assign fire resistance rating to concrete members through properly selecting a cover thickness to steel reinforcement or satisfying a minimum required dimension (width) [11], it is remarkable to note that these assigned fire ratings were developed based on fire tests carried out in 1960-1990s, and may not necessarily consider fire-induced spalling phenomenon [12].

Fire-induced spalling of concrete is often explained through different mechanisms. In the first mechanism, concrete spalls once evaporated moisture turns into pore pressure and builds up in micro-pores [6]. When stress generated from pore pressure exceeds the magnitude of tensile strength in concrete, spalling takes place. In other mechanisms, spalling is either induced through thermal gradients or through stresses of compressive nature resulting from restrained thermal dilation [13]. It is interesting to point out that there is enough experimental evidence to verify the validity of aforementioned mechanisms, as well as to contradict their rationales [14–20]. For example, while experiments carried out by Harmathy [21] indicate that spalling of concrete occurs early into exposure to standard fire (within 10–25 min), Song et al. [15] as well as Shah and Sharma [16] reported that spalling can also occur in the intermediate and later stages (at about 150 min) of exposure to the same fire scenario. Further, the addition of polypropylene and/or steel fibres was shown to reduce spalling in tests carried out by Kodur et al. [17], whereas tests conducted by

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Klingsch [18] show that the addition of such fibers did not positively reduce or eliminate fire-induced spalling in concrete. A more detailed and up-to-date discussion on conflicts between various mechanisms and previous studies and/or observations from fire tests with regard to concrete spalling can be found elsewhere [19,20].

Regardless of spalling mechanism, this phenomenon seems to be primarily governed by a number of factors [2,3,6,18,20]. Some of these factors are related to changes occurring at the material scale, geometric and loading features of concrete structural members, as well as those relating to fire intensity and exposure duration. In the past few decades, a number of attempts were carried out to develop approaches to evaluate and predict tendency of concrete to spall under fire conditions [11–20]. Most of these attempts followed a classical sense in which researchers investigated fire-induced spalling through testing and experimentation [13–17], theoretical/mathematical derivation [12], as well as numerical simulation [22]. While these studies managed to improve our understanding of spalling phenomenon, they continue to be impractical as they; 1) have complex procedure, 2) are hard to apply, and 3) have been only partially verified and against limited number of samples. Perhaps this is due to the fact that a cross examination of above discussion and previous works indicates that fire-induced spalling seems to be more of a random phenomenon rather than one of a deterministic nature.

Another reasoning, which is the driving force behind this work, is that the relation between governing factors and occurrence of concrete spalling has a multitude of dimensions and as such can be better understood through utilizing revolutionary methods. One such method is Machine Cognition (MC); a branch of machine intelligence (MI). This technology capitalizes on the notion that machines (i.e. computing tools) can be trained to evolve their own cognition process as to identify patterns and solutions to complex phenomena. Machine cognition has been extensively used in various fields (i.e. medical applications [23], space exploration [24]) and continues to show great potential in various engineering and societal applications.

A review of published studies shows that only a handful of researchers applied MI to investigate structural fire engineering problems. For example, Artificial Neural Networks (ANN), a sub-field of MI, has been used to develop temperature-dependent constitutive material models for construction materials [25,26], and to predict fire resistance and temperature rise in structural members [27] etc. Up to the author's knowledge, only one study has been carried out to examine fire-induced spalling of concrete through ANN [28]. In this study, a simple ANN was developed in order to qualitatively classify fire-induced spalling phenomenon in small-scale columns made of high strength concrete. This is considered to be one of the earliest attempts to apply MI technique to evaluate fire-induced spalling of concrete and as such suffers on a number of fronts, specifically to that associated with the limited number of observations used in developing the ANN, the fact that this ANN was only applicable to qualitatively classify spalling in RC columns made with one cross section, of same concrete mix, and did not develop tools/expressions to predict fire-induced spalling of RC columns.

In this study, a hybrid combination of contemporary MC techniques i.e. genetic algorithms (GAs), and symbolic regression (SR) are applied to derive expressions able of accurately predicting occurrence of fire-induced spalling as well as fire resistance of RC columns. The proposed expressions can be applied to various concretes, including normal strength, high strength and high performance concrete. In addition, the derived expressions can also be applied to RC columns with various features including different; cross sectional sizes, boundary conditions, steel reinforcement ratio, humidity levels, aggregate and fiber types, tie spacing and configuration, as well as subjected to concentric or eccentric loading. Furthermore, the MC-based expressions implicitly account for high temperature thermal and mechanical material properties of concrete and steel reinforcement, and as such do not require input of such properties nor special software. In total, five expressions were derived; four for predicting occurrence of fire-induced spalling in concrete columns and one for evaluating fire resistance of columns. The procedure adopted for developing these expressions, together with discussion on model development, validation, examination against other calculation methods, and limitations, are addressed in sub-sequent sections.

2.0 Factors Influencing Fire-Induced Spalling and Fire Resistance of RC Structures

When fire breaks out in a RC structure, cross-sectional temperature in surrounding structural member (say a column) slowly rises. This slow rise in temperature is a reflection of the good insulating (thermal) properties of concrete (i.e. low conductivity and high heat capacity, in addition to presence of small amounts of moisture). Thus, a significant amount of heat (thermal energy) is needed to elevate cross-sectional temperature in concrete. At the initial stage of fire, a thermal gradient develops in which the temperature at the exposed surface of concrete is much hotter than that at the level of embedded steel reinforcement or concrete core. This difference in temperature between outer and inner concrete layers reduces with extended fire exposure time i.e. as the cross section starts to uniformly heat up. While steel is a better conductor, the temperature in reinforcing steel can still be assumed to be similar to that of the surrounding concrete (as overall size/volume of reinforcement is insignificant as compared to the volume of concrete).

With the advent rise in cross-sectional temperature, the mechanical properties (strength and modulus) of both concrete and steel reinforcement starts to degrade. While such temperature-induced degradation is slow, as it corresponds to the slow temperature rise in concrete which comprises the majority of a RC section, this degradation could be accelerated by fire-induced effects such as cracking and most notably spalling of concrete. Spalling can be broadly grouped under two classes; explosive spalling and corner spalling [29]. Explosive spalling tends to occur violently and during the early phase of fire exposure [6]. This spalling is believed to be governed by pore pressure development/moisture migration and/or development of thermal gradients; especially once concrete layers reach a temperature of 220-280°C [29]. On the other hand, corner spalling mainly occurs gradually and along the corners of edged members (i.e. rectangular or square RC columns/beams) due to unrestrained thermal expansion in the transverse direction.

As discussed earlier, a complete understanding of fire-induced spalling is still not established yet, however, a thorough examination of published works identifies a collection of critical factors that seems to significantly influence occurrence of spalling and eventually fire resistance of RC members [2,3,6,29]. Some of these factors are concisely discussed herein.

2.1 Batch mix content (type of aggregate and fiber)

Aggregates are a major component in concrete mix. Two varieties of aggregates are often utilized in concrete batch mixes; carbonate (predominantly comprising limestone) and silicate (largely containing quartz). Of these two types, carbonate aggregate provides higher fire resistance of up to 10% that of silicate-based concrete. This arises from development of an endothermic reaction occurring around 700°C which lowers the rate of heat increase in concrete and decelerates strength deterioration [31].

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Inorganic/organic fibers are often added to batch mixture to improve performance and key characteristics. From the point of view of this study, two kinds of added fibers; steel and polypropylene fibers are of interest as they have been shown to reduce the magnitude of spalling. Supplementing a concrete mixture with steel fibers (of about 1.75% by weight) can mitigate spalling through two mechanisms; 1) by enhancing tensile strength of concrete, and 2) by slowing down the temperature-dependent deterioration of tensile strength. On the other hand, adding polypropylene fibers of about ~0.15% of concrete volume can also minimize fire-induced spalling as these fibers melt at 160–170°C emptying spaces that turn into additional pores which facilitate releasing and/or reducing concentration of pore pressure in concrete [30].

2.2 Properties of concrete (strength, density and humidity)

The nature of concrete, in terms of magnitude of its compressive strength can significantly influence fire-induced spalling and fire resistance of RC structural member. Higher concrete strength (greater than 70 MPa) is normally attained through addition of auxiliary fillers i.e. silica fume, fly ash etc. The addition of such fillers usually increases density and lowers permeability of concrete, and this in turn reduces formation of interstitial voids and promotes spalling [31]. Interestingly, fire tests on lightweight concrete have shown that this concrete is also vulnerable to fire-induced spalling. This has been credited to the higher moisture content in lightweight aggregate, which once evaporates can generate large amount of pressure [6]. On a similar front, high moisture content, often expressed by means of relative humidity, and exceeding 80% has been shown to increase concrete' vulnerability to spalling. This is especially true in case of structural members made of advanced concrete, as the low permeability of this type of concrete can entrap moisture for prolong periods.

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2.3 Geometric features (section shape/size and reinforcement configuration)

All being equal, enlarging the cross section of a concrete member positively improves fire resistance of that member. Still, increasing member size comes with an increased risk of explosive spalling as the volume of a RC member is directly proportional to the amount of moisture it can hold, as well as capacity to store thermal energy [22]. The configuration (shape) of a concrete section can also influence fire performance and resistance. For example, a square or rectangular RC column often has a poorer fire endurance than a circular RC column of equivalent cross sectional area. This is due to the fact the edges can easily attract heat (from both sides) as oppose to curved shapes and hence edged member experience faster rise in temperature [30]. This faster rise in temperature promotes faster degradation in mechanical properties.

The type and configuration of steel reinforcement are other factors grouped under geometric features of RC structural members. In the case of longitudinal reinforcement type, RC members reinforced with traditional (non-prestressed) reinforcement often achieve higher fire resistance and experience less susceptibility to spalling. This is unlike that of prestressed concrete members. The poor fire resistance of prestressed members mainly arises from three roots; 1) their slimmer cross section (lower thermal mass), 2) faster degradation of mechanical-based material properties in prestressed steel; as compared to non-prestressed steel, and 3) denser nature of prestressed concrete (i.e. higher tendency to entrap moisture [32]). The configuration of transverse reinforcements (i.e. ties) has also been noted to affect fire resistance and fire-induced spalling of RC members where RC columns with superior tie configuration (i.e. bent at 135°, and with closer tie spacing) achieving better fire performance [20].

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2.4 Loading conditions (magnitude of applied forces, boundary conditions and fire intensity)

The magnitude and arrangement of mechanical loading as well as of fire intensity can significantly influence fire-induced spalling and fire resistance of structures. In general, a loaded member is naturally vulnerable to spalling as applied loading generates an additional component of stress that amplifies the effect of steam-based pore pressure. These effects can further worsen, specifically in cases where the loading is applied eccentrically as eccentricity leads to developing tensile stresses on the side (column face) experiencing tensile forces. As heat is the main source of evaporating moisture content in a member, the intensity and duration of fire also influences fire resistance of concrete members. In particular, a fire with a rapid heating rate (i.e. tunnel or hydrocarbon fires) can thermally shock a fire-exposed member and such a shock can develop large thermal gradients, causing high thermal stresses as well as non-uniform expansion of exposed sides. Both of these effects can trigger spalling and/or reduce fire resistance of RC members.

While this discussion painted a broad picture of critical factors influencing fire response of concrete structures, it is worth mentioning that a more comprehensive assessment on parameters and effects that may influence fire performance of RC structures is spared herein for brevity but can be found in the following works [2,3,6,22,30,35,36].

3.0 Insights Into MC Model Development

Machine cognition (MC) is a specially designed computational technique that attempts to mimic human-like reasoning process to solve complex problems that may not be properly explained using traditional methods or those which would require advanced computing environments (software). This technique is suitable to understand complex phenomenon with large observations and/or number of variables and can specifically be used where there is an unclear

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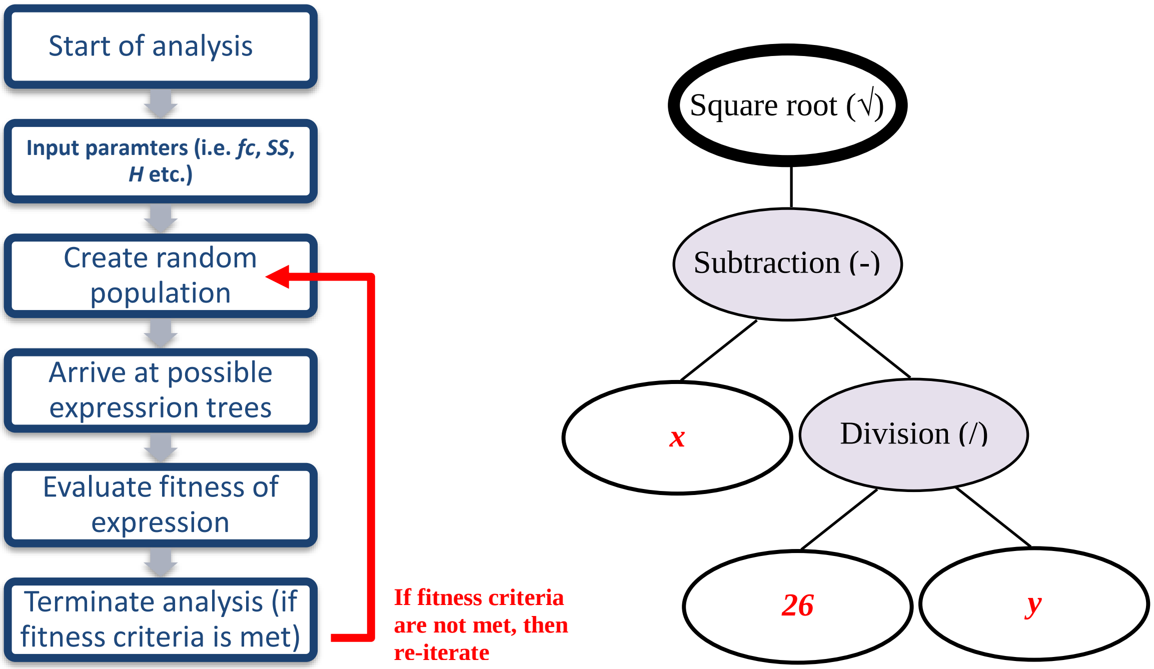
relation between such variables (inputs) and expected output(s). Machine cognition often utilizes evolutionary algorithms to learn patterns hidden in random points by carrying out systematic analysis. Once a pattern is discovered, this pattern comes to be the initial phase in solving the problem in hand through training and adaptive learning. More specifically, MC in this study primarily utilizes genetic programing, developed by Koza [33], as a tool to derive mathematical expressions. In this model, a string of a characters is arranged to characterize solutions. These solutions are expressed in terms of expression trees; a mathematical equation comprising of a tree-like data structure, where each node represents an expression. Genetic programing can be coded using a designer-approach in Matlab (e.g. GPTIPS code [34,35]) and can also be carried out using commercially available software such as Discipulus [36]. Such method has been applied towards developing predictive expressions on a number of phenomena in concrete structures in the last few years [37–39].

Genetic programing is a supervised learning process that attempts to express relations hidden between a number of factors through mimicking the natural selection process and following principles of Darwinian evolution. In these process, a predefined strings of expressions strive to arrive at mathematical representations to express a certain phenomenon. The analysis process starts with a random population of individuals often referred to as “trees” to represent a number of possible solutions through structural ordering of mathematical symbols. Thus, a possible solution is a ranked tree consisting of functions and terminals. In this study, a function ($\mathcal{F}$) may contains basic mathematical operations (+, ×, - etc.), power functions (^, log, exp), trigonometric functions (sin, cos, tan etc.), step and logistic functions among others. On the other hand, the terminal ($\mathcal{T}$) comprises of arguments as well as numerical constants and/or variables. Hence, a developed model has a tree-like configuration in which branches can extend from a function and end in a terminal. This tree can be converted into a "Karva-expression" (The first position in this expression denotes the root of the tree and the transformation process starts from the root and reads through the string layer by layer). A solution is deemed fit once such a solution satisfies certain fitness metrics such as coefficient of determination (R^2), correlation coefficient (R), mean absolute error (MAE) etc. At this stage the analysis terminates*. If fitness metrics were not satisfied, then this process is continued through a loop until the termination conditions are met. Figure 1 shows a flowchart of the implemented methodology as well as a typical solution tree.



(a) Flowchart of analysis procedure

(b) Typical tree representation for Karva-expression: $\sqrt{x - \frac{26}{y}}$

Fig. 1 Methodology followed in this study

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[*] It is worth noting that the use of a predefined generation number can also be used a termination criterion i.e. once a generation number (say of 2000) is reached, the analysis terminates.

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This study investigates two phenomena. The first being fire-induced spalling, and the second is fire resistance of RC columns. In order to evaluate these two phenomena, a thorough analysis of published fire tests [16,40–45], together with recommendations of notable works [2,3,6,20,29,46,47], was conducted to identify which parameters are recognized to be of critical importance and may govern fire-induced spalling and fire resistance of RC columns. The identified parameters were also selected keeping in mind that the outcomes of this study (i.e. predictive expressions) are to be highly accurate, and can be used without lengthy procedure, or need for complex computations, or special software/training and hence are useful for both, designers and researchers.

The identified critical parameters include: 1) concrete type, f_c, (normal strength, high strength and high performance), 2) cross sectional size, W, (203-400 mm), 3) boundary conditions, BC, (fixed-fixed, pinned-fixed, pinned-pinned), 4) stirrup (tie) spacing, SS, (75-400 mm), 5) stirrup configuration, SC, (traditional or hooked "bent at 135°"), 6) steel reinforcement ratio, r, (0.98-4.38%), 7) aggregate type, A, (silicate, carbonate, and light weight), 8) fiber type, f, (none, steel fibers or polypropylene fiber), and 9) initial humidity, H, (0-99%), as well as 10) magnitude, P, (0-5373 kN), and 11) arrangement of applied loading, ec, (concentric or eccentric with varying eccentricities from 0-40 mm). Thus, for all selected RC columns, above parameters were first collected from published fire tests [16,40–45]. In addition, the outcome of fire test on each column in terms of 1) magnitude of spalling (if column spalls), as well as 2) fire resistance of column (point in time when column fails under fire conditions) are also collected. Table 1 lists all identified factors along with their range (i.e. limits) of applicability and the full database used herein is also listed in the appendix.

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Table 1 Selected input parameters for MC-based expressions (and their range of applicability)*

Parameter/Case	**Input parameters**											**Outputs**
	Compressive strength of concrete (f_c), MPa	**Width of RC column (*W*), mm**	**Boundary conditions, *BC***	**Stirrup (tie) spacing, *SS*, mm**	**Stirrup configuration, *SC***	**Steel reinforcement ratio, *r*, %**	**Aggregate type, *A***	**Fiber type, *f***	**Initial humidity, *H***	**Magnitude of applied loading, *P*, kN**	**Arrangement of applied loading, *ec*, mm**	
Fire-induced spalling, *SP*	27 - 138	200 - 406	Fixed-fixed = 0 Pinned-fixed = 1 Pinned-pinned = 2	75 - 406	Traditional = 0 Hooked = 1	0.89 - 4.38	Silicate = 1 Carbonate = 2 Light weight = 3	No fibers = 0 Steel fibers = 1 Polypropylene fibers = 2	0 - 99	0 - 5373 kN	Concentric = 0 mm Eccentric (0 - 40 mm)	No spalling = 0, Spalling = 1 No spalling Minor spalling Major spalling
Fire resistance, *R*					-			-				Time to failure (min)

*For the sake of analysis, these inputs were normalized.

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Due to complications commonly arising in conducting fire experiments, availability of instrumentation and equipment, dissimilar approaches in documenting and reporting results of fire tests, a number of issues might evolve. For example, since actual measurements and/or tools to measure spalling rarely exist, if at all, spalling is often reported with qualitative terminology (as in minor or major spalling). However, the use of this terminology can be different from one researcher to another i.e. for one researcher spalling of 25% of surface area might be considered minor while for another, this magnitude can be major. In order to maintain coherence with previous works, the same terminology is also used herein i.e. if a test is reported to have minor spalling, this classification is also applied to the MC model, regardless of actual magnitude of spalling.

Further, in the event when a specific parameters such as "moisture content of concrete" is only reported in a small number of studies (but not all selected studies), this parameter was not selected to be a critical factor as to preserve uniformity between input data point since if it is to be used, tests reporting this parameter would need to: 1) be removed from developed databases which would reduce the overall number of input data points, or 2) be given "assumed" values which might jeopardize prediction capability of the MC-based expression. All in all, the developed MC approach is compliant enough to include other input parameters than those listed in Table 1 once information on a new variable is collected and added to the database.

The thought process behind the developed methodology stems back from fundamental engineering judgment, in which the following hypothesis is formed, "*if observations (i.e. spalling or fire resistance rating) obtained from a large number of fire tests is available, then perhaps it is possible to link such observations (outcomes) with the above identified factors through a relationship or set of relations*". Since there are eleven critical factors, then a relationship that connects such inputs to the final output(s) (being; spalling or fire resistance) is tedious and would require tremendous analysis/simulation to realize. As a result, a decision is made to explore the feasibility of solving such highly nonlinear relationships through integrating MC as this technology aims at deriving mathematical functions through logical understanding of a phenomenon and not just through satisfying numerical objectives often achieved through traditional analysis.

Furthermore, fire resistance analysis through MC is fundamentally different than that through simple calculation approaches or advanced methods i.e. finite element analysis. Traditional fire resistance analysis requires the development of two models; a thermal and structural. For such analysis, a number of parameters and appropriate high-temperature properties are assigned before the start of analysis. This analysis encompasses two steps. In the first step, rise in temperature and propagation within column’s cross section is calculated. This temperature is then input into the structural model to conduct stress analysis and evaluate failure of column. Both steps of analysis can be performed at sectional or member level; in a generic (ANSYS) or special finite element package such as SAFIR [48].

On the other hand, in MC, a fire related phenomenon can be evaluated through applying one expression without the need to compile temperature-dependent property, or carrying out complex/lengthy analysis procedure, or requiring special training/software/computing workstation. This can be achieved knowing that the outcome of a fire test is a function of fire scenario, magnitude of applied loading, as well as load bearing capacity of the tested column. For the sake of this study, the effect of the first two factors can be reduced to unity as all selected columns were tested under standard fires and the fact that applied loading during a fire test remains constant during fire (i.e. does not change) and hence only the magnitude of load (axial force) is of importance.

In contrast, the capacity of a typical column is governed by: 1) column's initial cross section, and 2) how strength of concrete and reinforcing steel degrades under elevated temperature. In this first case, the geometry of the column can be assumed to be constant throughout fire exposure, unless spalling occurs. Once spalling happens, the cross section of the column reduces, and this adversely affects (decreases) the capacity of the column. In the second case, the magnitude and rate of fire-induced deterioration in strength can be presumed to be similar for a given concrete mix and steel grade i.e. two identical RC columns made of normal strength concrete and subjected to similar fire and mechanical loading are likely to occur at the same point in time solely due to the fact that degradation in strength properties in both of these column will be similar. A similar conclusion can be drawn for columns made of high strength or high performance concrete.

As the outcome of fire tests (i.e. spalling or fire resistance) is known, then the developed MC model can relate all input parameters to the outcome of fire tests while implicitly accounting for high-temperature properties of concrete and steel and there will not be a need to input these properties to estimate spalling or fire resistance[†].

It is clear by now that the development of MC-based expressions entails assembling data points taken from large-scale fire tests on RC columns. A brief description of selected fire tests and related studies is provided herein as full details on collected tests, together with material properties and loading conditions etc., can be found in their respective references. For a start, the

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[†] While this rationale might seems optimistic as it simplifies the complex fire behavior of RC columns, Secs. 4 and 5 will examine the validity of this rationale in more details.

National Research Council of Canada (NRCC) has carried out extensive research programs to examine fire behavior of RC columns. Four of these programs are selected as they fit the theme of this study. In one early study, Lie and Woollerton [40] tested forty-one full sized RC columns under standard fire conditions. These tests varied a number of factors, for example: shape and cross-sectional area of column, percentage of longitudinal reinforcing steel, concrete compressive strength and type of aggregate, load intensity etc. The majority of these tests were conducted on square and rectangular columns with varying dimensions and only two identical circular concrete columns were tested. All specimens, except one column, had 38 mm thick concrete covers. On average, the compressive strength of concrete was 36 and 39 MPa, for carbonate and siliceous aggregate concretes. Steel reinforcement ratio as well as level of applied loading were varied between 2.19-3.97% as well as 0-90%, respectively.

At NRCC, Kodur et al. [41,42] also conducted fire tests on columns with similar features to that tested by Lie and Woollerton [40]. These columns were made of high strength and high performance concrete with compressive strength reaching 138 MPa. Kodur et al. [41,42] reported the high vulnerability of these tested columns to fire-induced spalling. Unlike tests carried out by Lie and Woollerton [40], Kodur et al. [41,42] varied other features such as spacing of ties, and heavily investigated the effect of eccentric loading. It should be noted that the studies carried out at NRCC are considered to be one of the most comprehensive tests conducted to date on fire resistance of RC columns. Shah and Sharma [16] conducted fire resistance experiments on eight RC columns, six of which were made of normal strength concrete and two of high strength concrete (HSC). These columns were longitudinally reinforced with eight steel rebars each of 16 mm diameter and were embedded behind 40 mm concrete cover. Other fire tests were also carried out by Myllymaki and Lie [43], etc. The appendix contains the complete database.

4.0 Performance and Validation of MC-Derived Expressions

Once the required data points were collected, these were input into the MC tool box in the software environment; Matlab [49]. The compiled input parameters were arbitrarily assembled such that no specific test/study was treated as a point of reference in order not to influence the MC analysis. In this software, candidate solutions are derived to describe fire-induced spalling and fire resistance of RC columns as a function of selected input parameters. Through genetic algorithms and symbolic regression, relations comprising of mathematical functions are derived and an optimum solution is achieved once it satisfies fitness conditions governed by error metrics i.e. difference (absolute or squared error) computed by subtracting predicted and measured values.

Out of all databases, 70% of data is used to train the MC-based model and 30% is evenly split to validate and then test the performance of the developed expressions [50,51]. Five expressions were derived, in which four can be used to predict occurrence and intensity of spalling. These expressions can be grouped under two approaches. In the first approach, one expression is derived using a "step" function which returns a binary output (i.e. zero for no spalling, and unity for spalling). In the second more inclusive approach, three expressions are derived using a "logistic" function. These expressions can be used to predict spalling occurrence and identify its intensity; "no spalling", "minor spalling" and "major spalling". Finally, a fifth expression is derived and this expression can be used to assess fire resistance of RC columns. These expressions, together with their fitness metrics, are listed in Table 2. The fitness metrics as obtained from these expressions are considered satisfactory by standards of other researchers [52,53]. These expressions do not have a form similar to that of commonly used calculation methods as MC-based expressions resemble the relation between input parameters and the propensity to spalling as a phenomenon (rather a physical quantity). For simplicity, these expressions along with collected data points are input into a spreadsheet that will be shared with fellow researchers upon request. It should be noted that two numerical examples are supplied in the appendix to illustrate how to properly collect input parameters and use proposed expressions to estimate vulnerability of a RC column to spall under fire conditions as well as its fire resistance. The validation and performance of these derived expressions are shown in Fig. 2.

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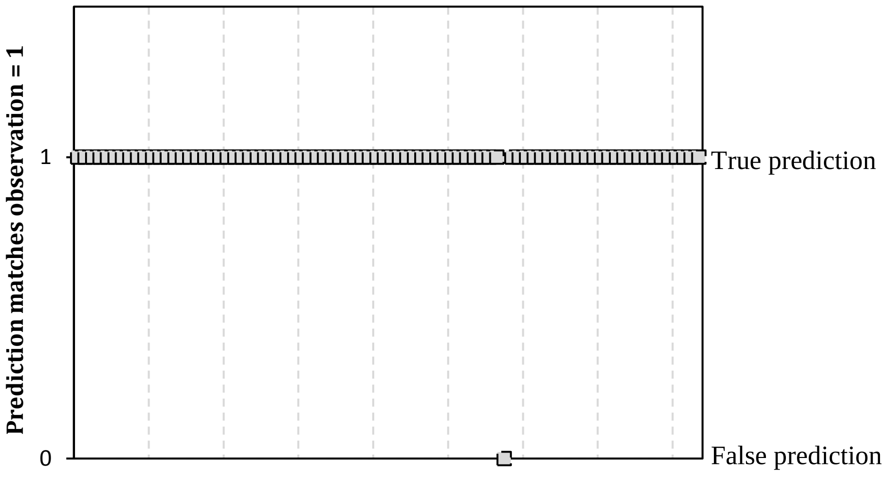
Table 2 MC-derived expressions to be used to evaluate fire response of RC columns.

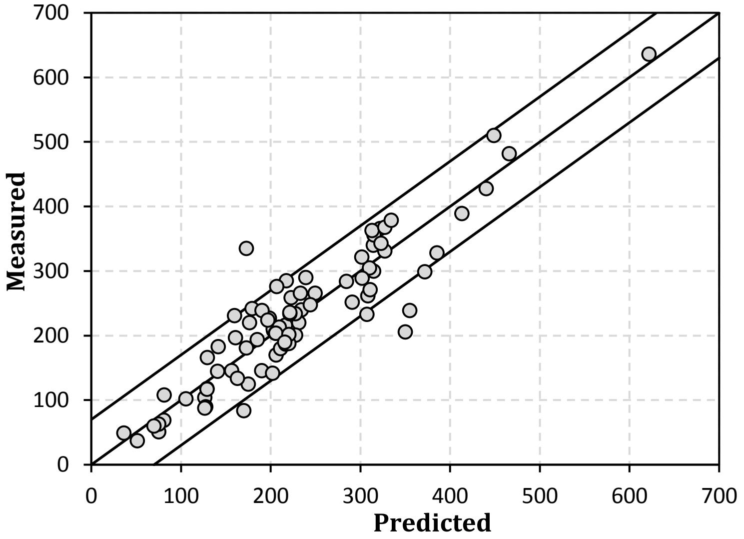
Case	**Remarks**		**Derived expressions**	**Coefficient of determination (R^2)**	**Correlation coefficient (R)**	**Mean absolute error (MAE)**
Fire-induced spalling	**See note no. 1***		$SP = step\left(f_c + ec + \tan\left(160.36 + \frac{0.01SSP}{H}\right) + \tan\left(\tan\left(160.54 + \frac{0.01SSP}{H}\right)\right) + \exp\left(BC + A + 2.18\cos\left(\frac{34.5f_c+34.5ec}{SC+f}\right)\right) - 75.8\right)$	0.946	0.973	0.013
	See note no. 2**	**No**	$SP = logistic\ (323.7 + 80\sin\left(\frac{10.3SSP}{H}\right) + 52.95\sin\left(\frac{87.3SSP}{H}\right) + 43\sin\left(2.77 + 52.95\sin\left(\frac{87.3SSP}{H}\right)\right) - 2.14f_c - 2.14ec - 2.14f - 55.63BC - 55.63SC - 55.63A)$	1	1	0
		Minor	$SP = logistic\ (\frac{-0.0948SSP}{H} + 103\sinh\left(\sin\left(\frac{0.807SSP}{H}\right) + \sin\left(\frac{0.01SSP\sin(\frac{0.807SSP}{H})}{H}\right) + \sin\left(\sin\left(5.69 + \frac{0.01fcSSP+0.01ecSSP+0.01SSfP}{H}\right)\right) - \sin\left(\frac{0.176SSP}{H}\right)\right) - 101\tan(0.22(BC + SC + A)^2)$			
		Major	$SP = logistic(21026\cos\left(\frac{0.01SSP}{H}\right) + 21025\sinh\left(0.703 + \frac{f_c+ec+f-89.9}{\exp(BC+SC+A)}\right) + 21025\cos\left(f_c + ec + f + \frac{f_c+ec+f-89.9}{\exp(BC+SC+A)}\right) + 21025\cos\left(3.52\cos(2 + 1.18f_c + 1.18ec + 1.18f + \frac{0.01f_cSSP+0.01ecSSP+0.01SSfP}{H}\right)$			
Fire resistance (min)	**Up to 10 hours of fire exposure**		$R = 144.06 + 85\sin(5.25^{BC})^{0.00077P} + 0.432f_c \times 3.96^{A\cos(A-0.024f_cW)} + \tan(88.55ec + 0.0769P - 0.0007755ecP) - 1.87\mathrm{asinh}(\frac{144.066}{\cos(3.492+9.747\times10^{-6}SS\,{f_c}^2}) - 8.669 \times 3.95^{A\cos(A-0.024f_cW)})\cos(3.49 + 9.747\times10^{-6}SS\,{f_c}^2) - 0.05H - 0.1r$	0.912	0.955	24.95

*This expression results in a binary output i.e., No spalling = 0, Spalling = 1

**These three expressions are to be applied simultaneously. The value closest to unity corresponds to the intensity of spalling (see Example 9.1 in the appendix).



(a) Fire-induced spalling

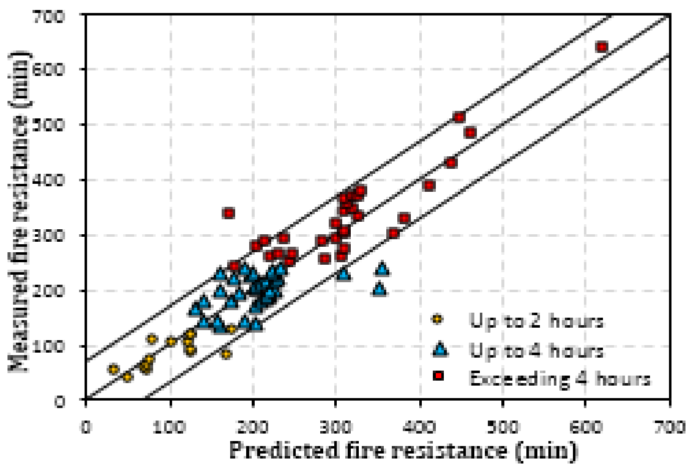


(b) Fire resistance

Fig. 2 Validation of the MC-derived expressions

It can be seen from above table as well as Fig. 2 that there seem to be a good correlation between predicted and measured data points where the bulk of the predicted data points fall within the ±10 bounds. Overall, the proposed expressions are easy to apply, can be used in a one step process, and accounts for various factors not commonly accounted for in currently available approaches such as that adopted in Eurocode 2 [54] or Australian code; AS 3600 [55], or that developed by Kodur and Raut [56]. Such factors include, tie spacing and configuration, humidity, high strength/high performance concrete, fiber content, eccentricity of applied loading, and lightweight aggregate. Further, existing approaches are also limited to certain geometric configurations (i.e. shapes; rectangular/square vs. circular, and sizes 200-600 mm), duration of fire exposure (~1-4 hours), concrete compressive strength (25-100 MPa), eccentricity, steel reinforcement ratio (1-4%). Other major advantages of the MC-predictive expressions are that they can accurately predict occurrence (and intensity) of fire-induced spalling and are applicable for up to 10 hours of standard fire.

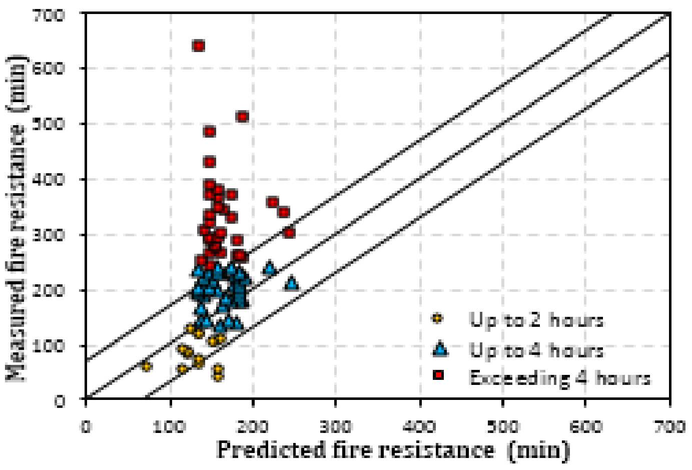
In order to further highlight the merit of MC, fire resistance predictions from the proposed expressions are also compared against that from existing methods namely those adopted by Eurocode 2 [54], and AS3600 [55], as well as that proposed by Kodur and Raut [56]. These predictions are plotted in Fig. 3. It can be inferred from plotted data that predictions from the proposed expression favorably agrees well with measured fire resistance as obtained in fire tests. On the other hand, predictions obtained from existing methods seem not to be able to fully capture fire behavior of RC columns especially in columns that experience spalling or that achieve fire resistance exceeding 4 hours. While AS 3600 seems to overestimate fire resistance in RC columns, an observation agrees with that also noticed by Kodur and Raut [56], both Kodur and Raut as well as Eurocode 2 methodology seems to adequately predict fire resistance in the range of 1 to 4 hours but then underestimate fire resistance for the columns failing beyond this range.



(a) MC-derived expression

$$R = 144.06 + 85\sin(5.25^{BC})^{0.00077P} + 0.432f_c \times 3.96^{A\cos(A-0.024f_cW)} + \tan(88.55ec + 0.0769P - 0.0007755ecP) - 1.87\operatorname{asinh}\left(\frac{144.066}{\cos(3.492+9.747\times10^{-6}SS\,f_c^{\,2})}\right) - 8.669 \times 3.95^{A\cos(A-0.024f_cW)}\cos(3.49 + 9.747\times10^{-6}SS\,f_c^{\,2}) - 0.05H - 0.1r$$

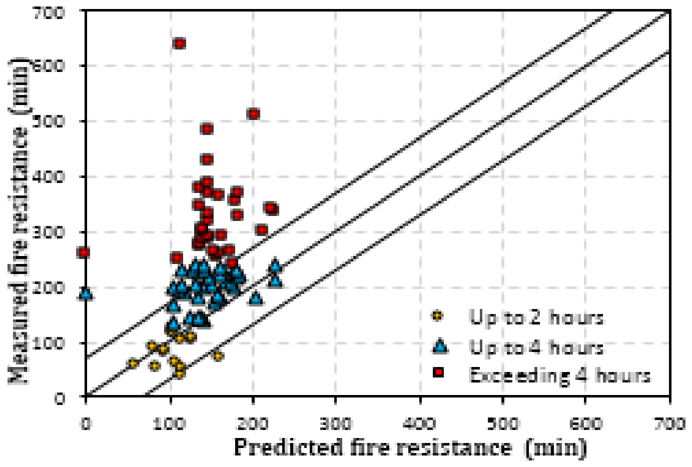
f_c = concrete type, W = cross sectional size,
BC = boundary conditions, SS = stirrup (tie) spacing,
SC = stirrup configuration, r = steel reinforcement ratio,
A = aggregate type, f = fiber type,
H = initial humidity, P = magnitude of loading,
ec = arrangement of applied loading.



(b) Eurocode 2 method

$$R = 120\left(\frac{R_{fi}+R_a+R_l+R_b+R_n}{120}\right)^{1.8}, \text{ and } R_{fi} = 83\left(1-\mu_{fi}\frac{1+\omega}{\frac{0.85}{\alpha_{cc}}+\omega}\right),\ \omega = \frac{A_s f_{yd}}{A_c f_{cd}}$$

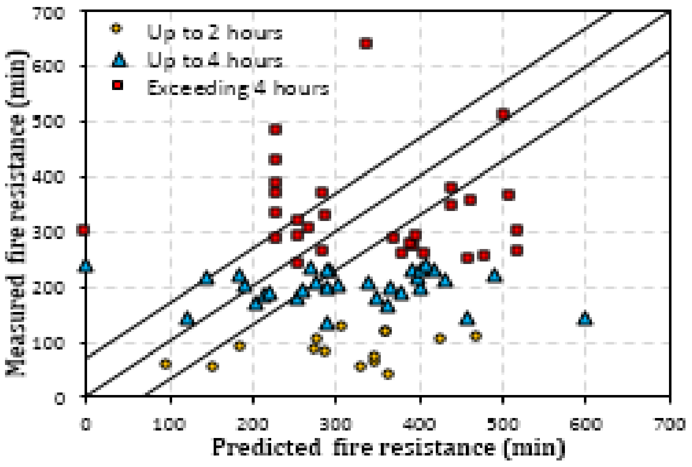
where,
R = fire resistance of column (min),
α_{cc} = coefficient for compressive strength,
$R_a = 1.6(a-30)$; a is the axis distance to the longitudinal steel bars (mm); 25 mm $\leq a \leq$ 80 mm,
$R_l = 9.6(5-l_{o,fi})$; $l_{o,fi}$ is the effective length of the column under fire conditions; 2 m $\leq l_{o,fi} \leq$ 6 m; values corresponding to $l_{o,fi}$ = 2 m give safe results for columns with $l_{o,fi}$ < 2 m,
$R_b = 0.09b'$; $b' = A_c/(b+h)$ for rectangular cross-sections or the diameter of circular cross sections,
$R_n = 0$, if 4 rebars are used, and 12 for more than 4 rebars.



(c) AS3600 method

$$R = \frac{k \times f_c^{1.3} \times B^{3.3} D^{1.8}}{N^5 \times N^{1.5} \times L_e^{0.9}}$$

where,
R = fire resistance of column (min),
k = a constant dependent on cover and steel reinforcement ratio (equals to 1.47 and 1.48 for a cover less than 35 mm and greater than or equal to 35 mm, respectively),
f_c = 28-day compressive strength of concrete (MPa),
B = least dimension of column (mm),
D = greatest dimension of column (mm),
N = axial load during fire (kN),
L_e = effective length (mm)



(d) Kodur and Raut approach

$$R = C_t\left(8 \times k_{cp} \times k_{ec}\left(30 - (S_R + 5) \times (L_R - 0.2)\right)\right)^{0.94}$$

where,
R = fire resistance of column (min),
C_t = 1.0 and 1.1 for siliceous and carbonate aggregate concrete respectively,
S_R is the slenderness ratio of the column,
L_R is the load ratio of the column,

$$k_{cp} = \frac{((C_s-82)\times(S_p+10.5)+870))}{390}$$

k_{ec} = 1 when eccentricity, E_c = 0, otherwise:

$$k_{ec} = \frac{((S_R-243)\times(E_c-768)-83250))}{99880}$$

Fig. 3 Comparison of fire prediction in RC columns using different methodologies

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5.0 Applicability of MC-derived Expressions to New Scenarios

To further validate the applicability of the proposed expressions, their predictions were also compared against results of fire tests that were not included in the developed databases. This ensures the validity of the proposed expressions in predicting new scenarios/conditions that they have not been exposed in the training phase. These scenarios include different cross-sectional shapes i.e. circular, cross (+) and tee (T).

While the derived expressions were developed for rectangular and square RC columns, these expressions are used to examine the behavior of a RC circular column tested by Lie and Woollerton [40]; Column 11h of the third series. This column has a diameter of 355 mm, steel ratio of 2.34%, and transverse spirals with a pitch of 54 mm. Applying above expressions shows that these expressions manage to capture possibility of minor fire-induced spalling which matches that occurring in the fire test, but slightly overestimate fire resistance of this column by about 11% (273 vs. 245 min). Fire resistance of this column was also examined using the currently adopted methods. This fire resistance was turned out to be 113.7, 464 and 86.2 minutes using Eurocode 2, AS 3600 and Kodur and Raut methods, respectively. These predictions are of much larger magnitude of error when compared to that obtained using MC.

Furthermore, two additional columns were selected from the experiments carried out by Xu and Wu [57]. These columns, C5 (with T-shape) and C9 (with +-shape), were made of siliceous concrete with compressive strength of 27 and 29.7 MPa, respectively. The columns also had a total width and depth of 500 mm, steel reinforcement ratio (1.51%), tie spacing of 200 mm, assumed humidity[‡] of 50%, loaded in a fixed-fixed configuration while being subjected to ISO 834 fire and loaded with 1602 and 1480 kN, respectively. These columns failed at 179 and 245 min, and predictive expressions estimated their failure at 196 and 221 min (within ± 9%)[§]. Further, Xu and Wu [57] reported that tested columns did not experience any spalling and this was also noticed through applying the derived expressions. Given that all above columns do not share exact features to that of the columns used to derive the MC expressions, validates the predictive capability of these expressions. The use of the derived expressions is best to be carried out for columns of similar features to those identified in Sec. 3.0 and listed in Table 1 as these columns were used in the MC development and derivation process. The reader is advised to note that the use of derived expressions in scenarios of outside their range of application still needs to be applied with caution.

6.0 Limitations and Future Improvements

Due to the fact that MC modeling heavily relies on the availability of data points (observations), which in this study are equivalent to those obtained from fire tests carried out on RC columns. From the point of view of this field, there is very limited information on fire tests, the MC-based expressions yield best performance in predicting behavior of RC columns that are of close proximity to those used in developing the models. This is one of the existing challenges as a close examination of the referenced fire tests indicates that majority of selected columns were tested in the mid-1980s and early 1990s. Furthermore, very few tests were ever undertaken on duplicated columns or on columns with comparable features/properties but with varying end

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[‡] Unfortunately, Xu and Wu [57] did not report value of humidity and hence it was assumed to be 50% based on a sensitivity analysis that was carried out. It is worth noting that for these particular columns, the humidity does not seem to affect their spalling tendency nor their fire resistance, primarily due to their relatively large size and moderate concrete strength.

[§] Fire resistance of these columns was not investigated using commonly used methods as these methods do not account for such unique cross sections.

restraints, concrete mixes etc. Since there has been significant advancement in concrete technology over the past three decades, the performance of modern concretes, including that of normal and high strength, might be different than those tested in earlier studies.

While the grade of steel does have an effect on the fire resistance of RC columns as this factor governs the axial capacity of a RC column at ambient conditions, from a practical point of view that involves fire, few points need to be realized: 1) the bulk of the RC columns tested by Lie and Woollerton [40], as well as Kodur et al. [41,42], and Dotreppe et al. [44] were reinforced with rebars with one grade of steel for main and transverse reinforcement as well as same tie diameter and concrete cover (i.e. from MC point of view, these factors are uniform across all columns and hence has a minor influence), and 2) steel reinforcement has a very small cross section (as well as volume) as compared to the concrete cross section (as such, temperature rise in steel rebars (of same or different grades) would be similar to that of the surrounding concrete). Since we still primarily use mild steel in the construction of columns, steels of this type often degrade at the same rate – a look into ASCE's or Eurocode 2's models show that material degradation of mild steels can be considered to follow one trend. Combing points 1 and 2 above, shows that from this work's point of view and given the number of tests surveyed and utilized, the grade of steel might not have a significant influence, but rather the ratio of steel, as it better relates to fire resistance is of importance[**]. This also agrees with the observation that the method adopted by the Australian code, as well as that developed by Kodur and Raut do not explicitly account for specific grades of steel. Further, mostly square and few rectangular RC columns were tested under fire conditions,

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[**] If/when a good amount of fire tests is carried out on columns reinforced with other grades, then the outcome of these tests will definitely be useful to update the derived expressions.

with lesser number of tests carried out on circular RC columns. As a result, the developed MC expressions have much higher accuracy when evaluating fire-induced spalling and fire resistance in case of square and rectangular columns as oppose to circular columns[††].

Another notion to consider is the fact that there continues to be a knowledge gap when it comes to quantifying magnitude of fire-induced spalling, i.e. minor or major. From this study’s perspective, the outcome of the derived expressions is to be utilized from a practical point of view, rather than quantitively. For example, if the derived expressions are applied in the design stage of a RC column and predict that such column is expected to undergo major spalling, then it is the duty of the designer to ensure including mitigation measures as to minimize the extent of damage such spalling might cause on the integrity of this column. For example, one designer might detail this column with hooked (135º) stirrups while another designer might consider adding a layer of thin steel mesh or add fibers etc. On the same note, identifying key factors that influence occurrence of fire-induced spalling and/or fire resistance of concrete structures is also of importance. Fortunately, MC has the ability to identify such important factors using a number of methods for instance: matrix correlation and principle component analysis (PCA) etc. The application of these methods, which is often applied in problems with high dimensionality, presents a new opportunity for interested researchers to further our knowledge base in this researcher area. The reader is to remember that the developed model can still be continually improved whether by incorporating safety factors or by feeding new data points obtained from future tests etc. and hence has the potential to be revised to incorporate a clear definition of spalling metrics (i.e. index, intensity etc.) is developed.

[††] A similar note can also be stated in the case of RC columns with embedded fibers.

Some of the aforementioned challenges can only be overcome through collaborative works to compile results of fire tests into databases, similar to the ones developed here or those available in literature (i.e. Underwriter Laboratories) etc. Further, this community can also plan a series of tests, to be specifically designed such that results of fire tests would be used in MI-based modeling, training, and validation, where some of these tests are to be primarily designed to examine influence of key parameters (i.e. porosity, moisture content, thermal gradient, rate of heating, sustained load during fire etc.) on spalling mechanism. An attractive resolution would be to build validated analytical and/or numerical models to generate data points on fire-induced spalling and fire resistance that can be used to train MC-models. On other note, the presented expressions are expected to undergo a series of improvements and calibration before being used in design applications, or in lieu of currently adopted methodologies. As stated earlier, all derived expressions along with collected data points are prepared into a spreadsheet that will be shared with other researchers upon request.

7.0 Conclusions

This paper integrates modern soft computing concepts such as machine cognition to derive expressions capable of predicting fire-induced spalling as well as fire resistance of RC columns. The proposed expressions are derived to be simple, of high accuracy and to implicitly account for temperature-dependent material degradation, and hence do not require input/collection of temperature-dependent material properties nor specialized software. The following conclusions could also be drawn from the results of this study:

- There is an urgent need to develop modern methodologies to allow accurate prediction of RC structures, especially under fire conditions. These approaches can conveniently be developed through modern concepts such as machine cognition/intelligence.

- Machine cognition analysis, through genetic programing, is able of accurately predicting fire-induced spalling and fire resistance of RC columns for exposure durations exceeding 4 hours.
- A few challenges seem to hinder integration of machine cognition applications, such as limited number of fire tests, differences in reporting fire test observations etc. These can be overcome through collaborative efforts.

Conflict of Interest

The author declares no conflict of interest.

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9.0 Appendix

This section illustrates two examples with procedure into applying the MC-derived expressions to evaluate susceptibility of a typical RC column to fire-induced spalling as well as fire resistance of the same column. This column was tested by Kodur et al. [41] as part of fire tests carried out at NRCC. This column, named HS2-7, achieved a fire resistance of 247 min after undergoing minor spalling; and has the following features:

1) Concrete type, f_c = 138 MPa (high strength concrete),
2) Cross sectional size, W = 406×406 mm (square),
3) Boundary conditions, BC = 2 (pinned ends),
4) Stirrup (tie) spacing, SS = 203 mm,
5) Stirrup configuration, SC = 2 (hooked; bent ties at 135°),
6) Steel reinforcement ratio, r = 2.47%,
7) Aggregate type, A = 2 (carbonate),
8) fiber type, f = 0 (none),
9) Initial humidity, H = 96.7%,
10) Magnitude, P = 4233 kN,
11) Arrangement of applied loading, ec = 27 mm (eccentric loading),

9.1 Example 1 – Fire-induced spalling

Two approaches can be applied to evaluate susceptibility of this column to spalling:

In the first approach, the output is binary (0 = no spalling, 1 = spalling occurs):

$$SP = step\left(f_c + ec + \tan\left(160.36 + \frac{0.01SSP}{H}\right) + \tan\left(\tan\left(160.54 + \frac{0.01SSP}{H}\right)\right) + \exp\left(BC + A + 2.18\cos\left(\frac{34.5f_c+34.5ec}{SC+f}\right)\right) - 75.8\right)$$

$$SP = step\Big(138 + 27 + \tan\Big(160.36 + \frac{0.01(203\times 4233)}{96.7}\Big) + \tan\Big(\tan\Big(160.54 + \frac{0.01(203\times 4233)}{96.7}\Big)\Big) + \exp\Big(2 + 2 +$$

$$2.18\cos\Big(\frac{34.5(138)+34.5(27)}{2+0}\Big)\Big) - 75.8\Big) = 1 \text{ (Spalling occurs)}$$

<u>In the second approach</u>, three expressions are to be applied simultaneously. The value closest to unity corresponds to the magnitude of spalling.

a) If no spalling is to occur:

$$SP = logistic\ (323.7 + 80\sin\Big(\frac{10.3SSP}{H}\Big) + 52.95\sin\Big(\frac{87.3SSP}{H}\Big) + 43\sin\Big(2.77 + 52.95\sin\Big(\frac{87.3SSP}{H}\Big)\Big) - 2.14f_c -$$

$$2.14ec - 2.14f - 55.63BC - 55.63SC - 55.63A)$$

$$SP = logistic\ \Big(323.7 + 80\sin\Big(\frac{10.3(203\times 4233)}{96.7}\Big) + 52.95\sin\Big(\frac{87.3(203\times 4233)}{96.7}\Big) + 43\sin\Big(2.77 +$$

$$52.95\sin\Big(\frac{87.3(203\times 4233)}{96.7}\Big)\Big) - 2.14(138) - 2.14(27) - 2.14(0) - 55.63(2) - 55.63(2) - 55.63(2)\Big) = 0$$

b) If minor spalling is to occur:

$$SP = logistic\ (\frac{-0.0948SSP}{H} + 103\sinh\Bigg(\sin\Big(\frac{0.807SSP}{H}\Big) + \sin\Bigg(\frac{0.01SSP\sin(\frac{0.807SSP}{H})}{H}\Bigg) + \sin\Big(\sin\Big(5.69 +$$

$$\frac{0.01fcSSP+0.01ecSSP+0.01SSfP}{H}\Big)\Big) - \sin\Big(\frac{0.176SSP}{H}\Big)\Bigg) - 101\tan(0.22(BC + SC + A)^2)$$

$$SP = logistic\ (\frac{-0.0948(203\times 4233)}{96.7} + 103\sinh\Bigg(\sin\Big(\frac{0.807(203\times 4233)}{96.7}\Big) + \sin\Bigg(\frac{0.01(203\times 4233)\sin(\frac{0.807(203\times 4233)}{96.7})}{96.7}\Bigg) +$$

$$\sin\Big(\sin\Big(5.69 + \frac{0.01\times 138\times(203\times 4233)+0.01\times 27\times(203\times 4233)+0.01(203\times 0\times 4233)}{96.7}\Big)\Big) - \sin\Big(\frac{0.176(203\times 4233)}{96.7}\Big)\Bigg) -$$

$$101\tan(0.22(2 + 2 + 2)^2) = 1$$

c) If major spalling is to occur:

$$SP = logistic(21026\cos\left(\frac{0.01SSP}{H}\right) + 21025\sinh\left(0.703 + \frac{f_c+ec+f-89.9}{\exp(BC+SC+A)}\right) + 21025\cos\left(f_c + ec + f + \frac{f_c+ec+f-89.9}{\exp(BC+SC+A)}\right) + 21025\cos\Big(3.52\cos(2 + 1.18f_c + 1.18ec + 1.18f + \frac{0.01f_cSSP+0.01ecSSP+0.01SSfP}{H}\Big)$$

$$SP = logistic(21026\cos\left(\frac{0.01(203\times4233)}{96.7}\right) + 21025\sinh\left(0.703 + \frac{138+27+0-89.9}{\exp(2+2+2)}\right) + 21025\cos\left(138 + 27 + 0 + \frac{138+27+0-89.9}{\exp(2+2+2)}\right) + 21025\cos\Big(3.52\cos(2 + 1.18(138) + 1.18(27) + 1.18(0) + \frac{0.01\times138\times(203\times4233)+0.01\times27\times(203\times4233)+0.01(203\times0\times4233)}{96.7}\Big) = 0$$

Thus, the outcome of expression in part (b) governs and minor spalling occurs; similar to that in the fire test.

9.2 Example 2 – Fire resistance

Fire resistance of this column can be evaluated using the following expression:

$$R = 144.06 + 85\sin(5.25^{BC})^{0.00077P} + 0.432f_c \times 3.96^{A\cos(A-0.024f_cW)} + \tan(88.55ec + 0.0769P - 0.0007755ecP) - 1.87\mathrm{asinh}\left(\frac{144.066}{\cos(3.492+9.747\times10^{-6}SS\,{f_c}^2}\right) - 8.669 \times 3.95^{A\cos(A-0.024f_cW)})\cos(3.49 + 9.747 \times 10^{-6}SS\,{f_c}^2) - 0.05H - 0.1r$$

$$R = 144.06 + 85\sin(5.25^2)^{0.00077(4233)} + 0.432f_c \times 3.96^{2\cos(2-0.024\times138\times406)} + \tan\big(88.55(27) + 0.0769(4233) - 0.0007755(27\times4233)\big) - 1.87\,\mathrm{asinh}\left(\frac{144.066}{\cos(3.492+9.747\times10^{-6}(203)\,138^2}\right) - 8.669 \times 3.95^{2\cos(2-0.024\times138\times406)})\cos(3.49 + 9.747\times10^{-6}(2)\,138^2) - 0.05(96.7) - 0.1(2.47) = 244.3\text{ min}$$

(Compared to 248 min as observed in fire test).

The same analysis in Examples 9.1 and 9.2 can also be carried out using the attached spreadsheet.

9.3 Database [59]

Study	Sp. Num.	f_c (MPa)	W (mm)	ec (mm)	r (%)	BC	SS (mm)	f	H (%)	A	P (kN)	R (min)	SP	SPI	R_{pred} (min)	R/Rpred
[40]	1a	34.2	305	0	2.19	0	305	0	5	1	0	240	N	N	234.06	0.98
[40]	2a	36.9	305	0	2.19	0	305	0	15	1	1333	170	N	N	206.17	1.21
[40]	3a	34.2	305	0	2.19	0	305	0	70	1	800	218	N	N	225.30	1.03
[40]	4a	35.1	305	0	2.19	0	305	0	63	1	711	220	N	N	231.38	1.05
[40]	5g	40.7	406	0	2.47	0	406	0	9	1	0	300	N	N	314.75	1.05
[40]	6g	42.3	203	0	2.75	0	203	0	29	1	169	180	N	N	210.88	1.17
[40]	7a	36.1	305	0	2.19	0	305	0	74	1	1067	208	N	N	203.14	0.98
[40]	8a	34.8	305	0	2.19	0	305	0	74	1	1778	146	N	N	190.12	1.30
[40]	9a	38.3	305	0	2.19	0	305	0	75	1	1333	187	N	N	216.66	1.16
[40]	10b	40.9	305	0	2.19	0	305	0	75	2	800	510	N	N	448.82	0.88
[40]	11b	36.9	305	0	2.19	0	305	0	75	2	1067	366	N	N	321.95	0.88
[40]	12b	39.9	305	0	2.19	0	305	1	76	2	1778	216	N	N	216.18	1.00
[40]	1e	41.6	305	0	2.19	1	305	2	65	1	342	340	Y	MN	314.51	0.93
[40]	2e	43.6	305	0	2.19	0	305	0	75	1	1044	201	N	N	227.65	1.13
[40]	3e	35.4	305	0	2.19	0	305	0	75	1	916	210	N	N	202.84	0.97
[40]	4d	52.9	305	0	2.19	0	305	0	75	1	1178	227	N	N	198.66	0.88
[40]	5d	49.5	305	0	2.19	0	305	0	75	1	1067	234	N	N	227.52	0.97
[40]	6c	46.6	305	0	2.19	0	305	0	79	3	1076	188	N	N	220.44	1.17
[40]	7c	42.5	305	0	2.19	0	305	0	80	3	947	259	N	N	222.69	0.86
[40]	8f	42.6	305	0	4.38	0	305	0	61	1	978	252	N	N	290.78	1.15
[40]	10g	38.8	406	0	2.47	0	406	0	80	1	2418	262	N	N	308.37	1.18
[40]	11g	38.4	406	0	3.97	0	406	0	75	1	2795	285	N	N	217.44	0.76
[40]	12g	46.2	406	0	3.97	0	406	0	68	1	2978	213	N	N	209.54	0.98
[40]	1i	39.6	305	0	2.19	1	305	0	60	1	800	242	N	N	179.32	0.74
[40]	2i	39.3	305	0	2.19	1	305	0	64	1	1000	220	N	N	176.33	0.80
[40]	3k	39.9	305	25	2.19	0	305	0	56	2	1000	181	N	N	172.96	0.96
[40]	4j	37.6	305	0	2.19	0	305	0	45	2	1067	328	Y	MN	385.20	1.17
[40]	5h	42.5	305	0	2.22	0	305	0	65	1	1413	356	N	N	315.00	0.88
[40]	6h	42.1	203	0	1.22	0	203	0	58	1	756	335	N	N	172.74	0.52
[40]	14k	37.9	305	25	2.19	0	305	0	25	1	1178	183	N	N	141.36	0.77
[42]	HSC2	126.5	406	0	2.42	2	406	0	67	2	2913	204	Y	MJ	205.25	1.01
[42]	HSC3	99.7	406	0	2.42	0	406	0	69	1	3080	239	Y	MJ	190.18	0.80
[42]	HSC4	89.6	406	0	2.42	2	406	0	61	2	2934	145	Y	MJ	140.62	0.97
[42]	HSC5	86	406	0	2.42	0	406	0	86	1	2406	224	Y	MJ	196.59	0.88
[42]	HSC6	96	406	0	2.42	0	406	0	57	2	4919	104	Y	MJ	126.49	1.22
[42]	HSC7	119.7	305	0	1.72	0	152	0	50	2	1979	266	Y	MJ	249.45	0.94
[42]	HSC8	119.7	305	0	1.72	0	76	0	68	2	2363	290	Y	MJ	239.25	0.82
[42]	HSC9	119.7	305	0	1.72	0	76	0	64	2	2954	266	Y	MJ	233.07	0.88
[42]	HSC10	119.7	305	25	2.42	2	76	0	64	2	2954	49	Y	MJ	36.33	0.74
[41]	TNC1	40.2	305	0	2.18	0	145	0	90	1	930	276	N	N	206.63	0.75
[41]	TNC2	40.2	305	0	2.18	0	145	0	51	1	1500	204	Y	MJ	205.62	1.01
[41]	TNC3	40.2	305	25	2.18	2	145	0	92	1	1000	90	N	N	127.51	1.42
[41]	THC4	99.6	305	0	2.18	0	145	0	78	1	2000	202	Y	MJ	220.19	1.09
[41]	THC5	99.6	305	0	2.18	0	145	0	58	1	2000	234	Y	MJ	221.19	0.95
[41]	THC6	99.6	305	0	2.18	0	145	0	61	1	3000	190	Y	MJ	215.61	1.13
[41]	THC7	72.7	305	0	2.18	0	145	0	93	2	1300	363	Y	MJ	313.09	0.86
[41]	THC8	72.7	305	0	2.18	0	145	0	67	2	2000	305	N	N	310.23	1.02
[41]	THC9	72.7	305	25	2.18	2	145	0	94	2	1200	125	Y	MJ	175.00	1.40
[41]	THS10	89.1	305	0	2.18	0	145	0	80	1	1800	239	Y	MJ	355.13	1.49
[41]	THS11	89.1	305	0	2.18	0	145	0	99	1	2200	206	Y	MJ	350.04	1.70
[41]	THS12	89.1	305	25	2.18	2	145	0	99	1	1500	84	Y	MJ	170.16	2.03
[41]	THP13	86.6	305	0	2.18	0	145	0	94	1	1800	271	N	N	310.78	1.15
[41]	THP14	86.6	305	0	2.18	0	145	0	85	1	2200	233	Y	MJ	307.10	1.32
[41]	THP15	86.6	305	25	2.18	2	145	0	97	1	1500	88	Y	MJ	126.62	1.44
[16]	MBS50	34	300	0	1.78	0	200	0	56	2	1170	284	N	N	284.61	1.00
[16]	MBS75	34	300	0	1.78	0	150	0	55	2	1170	331	N	N	327.34	0.99
[16]	MBS100	34	300	0	1.78	0	75	0	56	2	1170	428	N	N	440.42	1.03
[16]	MBS150	34	300	0	1.78	0	150	0	56	2	1170	368	Y	MJ	327.29	0.89
[16]	MBST150	34	300	0	1.78	0	100	0	59	2	1170	389	N	Minor	413.33	1.06
[16]	MBS200	34	300	0	1.78	0	50	0	55	2	1170	482	Y	MJ	465.92	0.97

[16]	M6S150	63	300	0	1.78	0	150	0	48	2	1858	289	Y	MJ	301.77	1.04
[16]	M6ST150	63	300	0	1.78	0	150	0	49	2	1858	322	Y	MN	301.72	0.94
[41]	HS2-1	85	406	0	2.47	0	203	0	69	2	3895	299	N	N	371.74	1.24
[41]	HS2-2	85	406	0	2.47	0	305	2	58	2	4328	343	Y	MJ	323.04	0.94
[41]	HS2-3	85	406	0	2.47	0	406	0	61	2	4328	379	Y	MJ	334.28	0.88
[41]	HS2-4	114	406	0	2.47	0	203	0	57	1	4567	146	Y	MJ	156.45	1.07
[41]	HS2-5	114	406	0	2.47	0	305	0	77	1	5373	108	Y	MJ	81.19	0.75
[41]	HS2-6	114	406	0	2.47	0	406	0	98	1	3546	142	Y	MJ	202.27	1.42
[41]	HS2-7	138	406	27	2.47	2	203	0	96	2	4233	248	Y	MJ	244.31	0.99
[41]	HS2-8	138	406	27	2.47	2	305	0	93	2	4981	118	Y	MJ	129.10	1.09
[41]	HS2-9	138	406	27	2.47	2	305	0	92	2	4981	117	Y	MJ	129.15	1.10
[41]	HS2-10	138	406	27	2.47	2	406	0	96	2	4981	166	Y	MJ	129.50	0.78
[58]	NSC0	28	300	0	2.28	1	300	0	77	2	544	236	Y	MJ	221.48	0.94
[58]	NSC1	28	300	20	2.18	1	300	0	61	2	532	102	Y	MJ	105.52	1.03
[58]	NSC2	32	300	20	2.28	1	300	0	42	2	579	231	Y	MJ	159.63	0.69
[58]	NSC3	31	300	40	2.28	1	300	0	57	2	567	134	Y	MJ	162.83	1.22
[58]	NSC4	27	300	20	2.28	1	150	1	49	2	544	194	Y	MJ	184.82	0.95
[58]	NSC5	31	300	40	2.28	1	150	1	57	2	567	197	Y	MJ	160.58	0.82
[58]	HSC0	69	300	0	2.28	1	300	2	78	2	1008	69	Y	MJ	80.86	1.17
[58]	HSC1	58	300	20	2.18	1	300	0	47	2	892	51	Y	MJ	75.12	1.47
[58]	HSC2	69	300	20	2.28	1	300	0	45	2	973	37	Y	MJ	51.35	1.39
[58]	HSC3	67	300	20	2.28	1	150	0	51	2	996	636	Y	MJ	621.77	0.98
[58]	HSC4	60	300	40	2.28	1	150	0	41	2	892	63	Y	MJ	75.20	1.19
[43]	C	37.8	300	0	0.89	2	240	0	99	1	1400	60	Y	MJ	69.71	1.16
															Average	1.04
															Standard deviation	0.23
															Coff. of Variation (%)	22.24

SP: Spalling occurrence→Y: Yes, N: No.; *SPI*: Spalling intensity→MJ: Major spalling, MN: Minor spalling.
A: Aggregate type→Silicate = 1, Carbonate = 2, Lightweight = 3.; *f*: Presence of fibers→No fibers = 0, Steel fibers = 1, Polypropylene fibers = 2.