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Properties and Material Models for Construction Materials Post Exposure to Elevated Temperatures

M.Z. Naser[1], V.A. Uppala[2]

Abstract

Temperature rise, as in the case of fire, severely damages the properties of construction materials and imposes temperature-induced degradations that alter their microstructure and characteristics. As such, practitioners often struggle when assessing residual state of a fire-damaged structure especially due to the lack of insights into residual (post-fire) properties of construction materials. With the hope of narrowing this knowledge gap, this study presents an approach to derive residual material models for a variety of construction materials such as normal strength concrete (NSC), high strength concrete (HSC), ultra-high performance concrete (UHPC), mild steel (MS), high strength steel (HSS), cold formed steel (CFS), stainless steel (SS), glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP). This approach leverages a hybrid combination of two machine learning (ML) techniques (artificial neural networks (ANN) and genetic algorithms (GA)) to derive specifically tailored material models capable of tracing the post-fire behavior of construction materials. When implemented, the proposed material models could enable proper and unified assessment of fire-damaged structures.

Keywords: Residual properties; post-fire conditions; material models; artificial neural network (ANN); genetic algorithm (GA); machine learning (ML).

1.0 Introduction

Fire is considered to be an extreme loading condition with the potential to severely damage construction materials, and by extension, structural components and systems. This effect is due to the fact that properties of construction materials undergo drastic microstructural thermo-physio-chemical degradations under elevated temperatures and may never regain their pre-fire properties even after cooling down to ambient conditions. Since such degradations often have an adverse impact on buildings' integrity, the risk of extensive structural damage to buildings must be minimized in order to allow safe evacuation and proper firefighting operations, as well as ensure future re-usability of the structure (Mahamid et al., 2019). It is interesting to note that recent statistics show how fire-induced collapse of structures is rare and hence properly assessing the residual state of a fire-damaged structure becomes of utmost importance to enable adequate repairs and retrofitting (Raouffard and Nishiyama, 2016).

In general, this assessment process comprises a rather complex procedure that requires a thorough knowledge on fire characteristics, structure's layout, load pathing, and most importantly residual properties of construction materials (Kodur and Agrawal, 2016). In other words, the residual capacity of a fire-damaged structure can be determined if/once information on post fire mechanical properties i.e. compressive/yield strength and Young's modulus of elasticity, is available or

[1]PhD, PE, Glenn Department of Civil Engineering, Clemson University, Clemson, SC, USA, E-mail: mznaser@clemson.edu, m@mznaser.com, Website: www.mznaser.com
[2]EIT, Former graduate student at Glenn Department of Civil Engineering, Clemson University. Currently, Bridge Engineer, TranSystems Corporation, Charleston, SC.

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known. Unfortunately, most fire codes and standards do not provide specific guidance to properly assess residual structural capacity of fire-damaged structures (ACI216.1, 2014, ECS, 2005a, b). Only few recommendations and rule of thumbs exist, and these tend to leverage outdated assumptions and extend provisions used in the traditional analysis and design procedure at ambient conditions in order to estimate post-fire residual capacity (Hager, 2014, McCallum et al., 2006).

Whether simplified (cross-sectional analysis) or advanced (finite element simulation) methods are used to assess post-fire capacity of a structure, these methods require the input of representative properties that accurately resemble the state of construction materials in the aftermath of a fire event (Han et al., 2005). Unfortunately, such information is not always readily available, as it requires specifics on actual materials used in construction as well as on characteristics of that particular fire incident (i.e. duration, maximum temperature reached, cooling phase etc.). As a result, practitioners often end up estimating such properties either through engineering judgment (i.e. color changes in concrete, char depth in wood etc.) or following assumptions adopted in fire design codes and standards (e.g. Eurocodes suggest using residual properties that are reduced by up to 10% of values at target temperatures under heating conditions (CEN, 2002)).

However, one should note that such assumptions are rough estimates on generic materials and may not be representative of those comprising a structural system in a fire-damaged structure. Furthermore, these estimates are only available for common construction materials (i.e. normal strength concrete, mild steel etc.) and may not be extended to modern materials such as ultra-high performance concrete (UHPC), high strength steel (HSS) etc. which are being used nowadays on a more frequent basis. Adopting the aforenoted assumptions in design scenarios may prove inconvenient, especially in new high-rise buildings which seem to be more vulnerable to fire (i.e. due to the presence of higher fuel densities, utilization of composite façade/panels etc.) and tendency to use modern construction materials (i.e. composites) (Quintiere, 2011).

In order to better grasp the post-fire response of construction materials, a number of researchers carried out testing programs to evaluate residual properties under simulated post-fire conditions. In one study, Botte and Caspeele (2017) conducted tests on normal strength concrete (NSC) specimens and reported that the compressive strength can be reduced to 16% after the specimens cooled down from an exposure to 800°C. Similarly, Abdul Rahim et al. (2013) conducted tests on specimens made of high performance concrete (HPC) and noted how the compressive strength reduces to around 30% after reaching a temperature of 800°C. A more modern type of concrete, UHPC, was also tested by Way and Wille (2015). These researchers showed how compressive strength of UHPC can drastically drops to 37% of its room temperature value after an exposure to 700°C.

Similar works also examined residual properties of metallic and composite materials used in construction applications. In one study, Zhou et al. (2019) noted that yield strength and Young's modulus of elasticity of mild steel reduce to around 95% and 98% following an exposure to 600°C and 800°C, respectively. Wang et al. (2018) tested the same properties for high strength steel (HSS) and reported residuals at 64% and 84% after 900°C. Other metallics were also tested including cold-formed steel (CFS) and stainless steel (SS) (He et al., 2019, Kesawan et al., 2018). Kesavan et al. (2018) conducted tests on CFS and reported that the yield strength and Young's modulus of elasticity to reduce around 75% and 84% following 700°C and 800°C, respectively. In the case of SS, He et al. (2019) showed how properties of this material seem to be slightly affected in the aftermath of fire. On a parallel note, only a handful of studies tested post-fire exposure behavior of glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) often used in strengthening and retrofitting applications. Overall, the open literature seems to be clearly lacking on the front of material tests carried out to examine residual properties – unlike the case for material tests conducted under heating conditions (Kodur and Agrawal, 2016, Wang et al., 2018, Zhou et al., 2019).

In order to bridge this knowledge gap, this paper proposes an intelligent approach to develop residual material models for a variety of construction materials including normal strength concrete (NSC), high strength concrete (HSC), ultra-high performance concrete (UHPC), mild steel (MS), high strength steel (HSS), cold formed steel (CFS), stainless steel (SS), glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP). To generate these material models, an extensive data collection has been carried out wherein this dataset was then analyzed using a hybrid combination of two machine learning (ML) techniques namely Artificial neural network (ANN) and genetic algorithms (GA). This paper hypothesizes that integrating machine learning can aid in developing unified residual material models and could also accelerate ongoing standardization efforts seeking to standardize fire assessment procedure including residual assessment of fire-damaged structures.

2.0 A critique on collected material models obtained from residual tests

Testing for residual properties of construction materials often utilizes small scale specimens (i.e. cubes and cylinders in case of concretes and coupons in case of metallics and composites). These specimens are prepared and then heated using furnaces or electric ovens with a predefined heating rate (i.e. 5°C/min) to reach a predefined temperature (say 600°C) at which they are held for a predetermined duration (e.g. 2 hours)[3]. Once uniformly heated, specimens are then left to cool down to ambient conditions while awaiting testing. Specimens can be left to cool down naturally or can be cooled down by submerging in water (Kodur and Harmathy, 2016). It should be noted that the majority of the surveyed tests herein examined loaded specimens that were cooled naturally[4] (Annerel, 2010, Behloul et al., 2002, Bingöl and Gül, 2009, BSI, 2004, Chan et al., 1999, De Chefdebien et al., 2007, Choi and Chung, 2016, Diederichs and Mertzsch, 2008, Felicetti and Gambarova, 1998, Felicetti and Meda, 2005, Foster and Bisby, 2008, Gao et al., 2018, Gunalan and Mahendran, 2014, Hawileh et al., 2015, He et al., 2019, Hou et al., 2017, Huang and Young, 2017, Jianfeng and Pingzhou, 2010, Kesawan and Mahendran, 2018, Kodur et al., 2017, Lee et al., 2008, Lu et al., 2016, Mindeguia et al., 2007, Missemer, 2011, Poon et al., 2001, Qiang et al., 2012, 2013, Rahim et al., 2013, Hamad et al., 2017, Sajid and Kiran, 2018, Singh and Singh, 2019, Spagnuolo et al., 2018, Wang et al., 2014; Way and Wille, 2015, Xiong and Liew, 2015, Yu et al., 2019, Zhang et al., 2009, Zheng et al., 2012b, a, Zhou et al., 2019).

[3] It is worth noting that specimens can be mechanically loaded during heating.
[4] It should be stressed that despite the fact that cooling of structures (as a result of firefighting) employs water as a main extinguishing agent, the effect of water cooling has been much less investigated in the literature (Botte and Caspeele, 2017).

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While the above describes the general procedure of material-based testing, one should note that published works did not seem to follow a standardized testing procedure as the these works reported different specifics with regard to specimen size, boundary conditions, particular heating/cooling rates etc. (Bingol and GulRustem, 2007, Durgun and Sevinç, 2019). This has resulted in a wide scatter in the outcome of these tests. As such, measured properties for similar, and sometimes identical, materials tend to vary across a wide range. Here we critique observations obtained from some of the reviewed material tests – with especial consideration to the mechanical properties[5].

For example, Chan et al. (1999) investigated the effect of post fire cooling on properties of 100 mm wide cubic concrete specimens and noted how exposing such specimens to temperature range between 25-400°C resulted in limited damage as opposed to temperatures in higher ranges. Similarly, Botte and Caspeele (2017) also heated 100 mm cubes made of NSC at a rate of 1°C/min till reaching three maximum temperatures 157°C, 350°C, and 600°C. These researchers investigated different cooling rates and reported how residual compressive strength property is significantly influenced by the cooling rate and process. In another study, Bingol et al. (2007) examined NSC cylinders measuring at 100 mm diameter with 200 mm in height. In these tests, the peak temperatures were maintained for three hours – unlike those which were maintained for 15 hours and tested by Botte and Caspeele (2017). Due to these differences in testing procedure, the outcome of these two programs was different (see Fig. 1). In fact, a closer look into Fig. 1a shows that loss in compressive strength of NSC reported by Botte and Caspeele (2017) at 700°C was 28%, while this loss was reported at 42% in the work of Bingol et al. (2007). Way and Wille (2015) reviewed post fire material tests on UHPC and reported slight improvement in temperature range of 150-300°C due to increased pozzolanic reaction, which is called as the "internal autoclave" (Ali et al. 2004). The behavior of this concrete is then often accompanied with degradation in compressive strength in the range of 15% to 51% after exposed to 700°C[6], while the Young's modulus property varies with a wider range from 10% to 50% following 600°C. Similar observations can also be noted by comparing other works and these can be attributed to differences in aspects regarding testing methods, concrete composition, specimen sizes etc. It is worth noting that Naus (2010) compiled a comprehensive review on the properties of concrete materials during and post fire conditions – some of which were used in this study and these are plotted in Fig. 1b-d.

[5] Tests carried out to examine thermal properties of construction materials have rarely been reported and hence these will be considered separately and in a future work. The material properties of interest to this work include: compressive strength for concretes, yield strength for metallics, tensile strength for composites and elasticity properties for all of these materials.
[6] It is interesting to note that measurements on residual compressive strength property of UHPC and HSC are very limited beyond an exposure to 700°C, probably due to the unstable structure and propensity of fire-induced spalling of these concretes.

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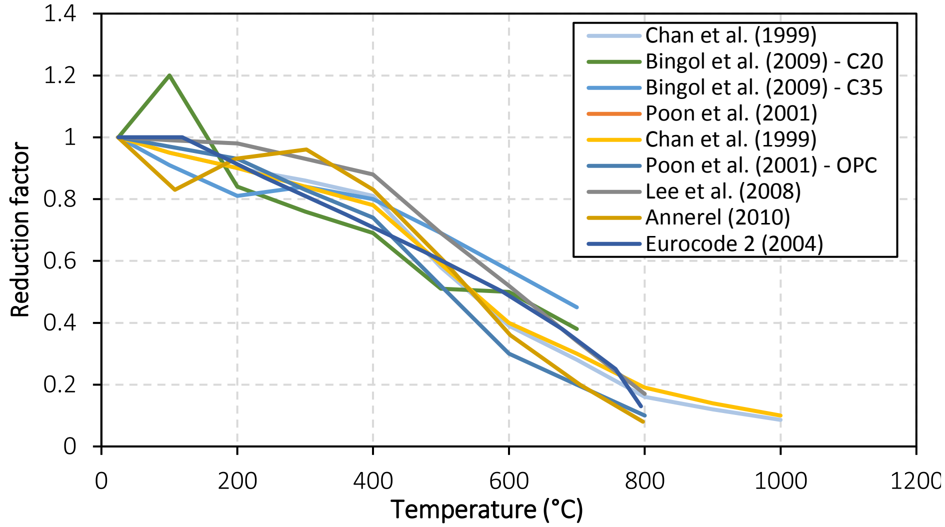
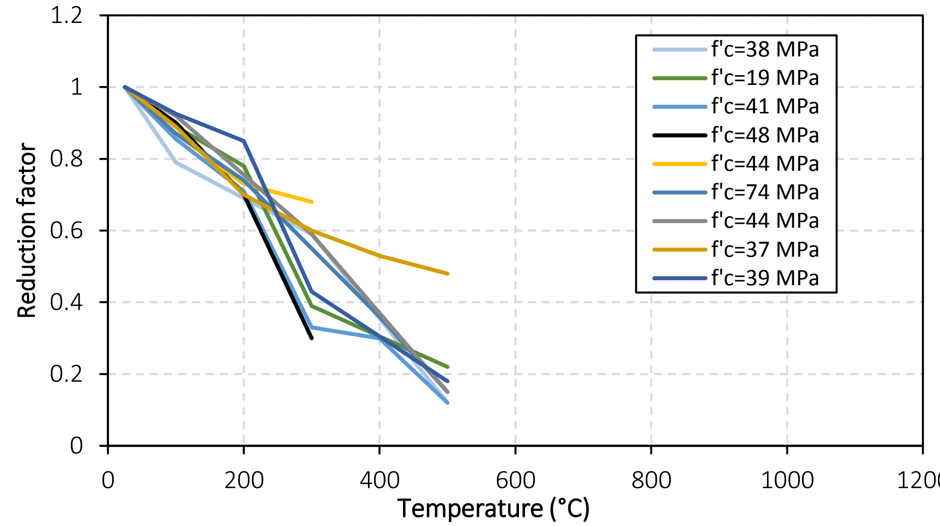
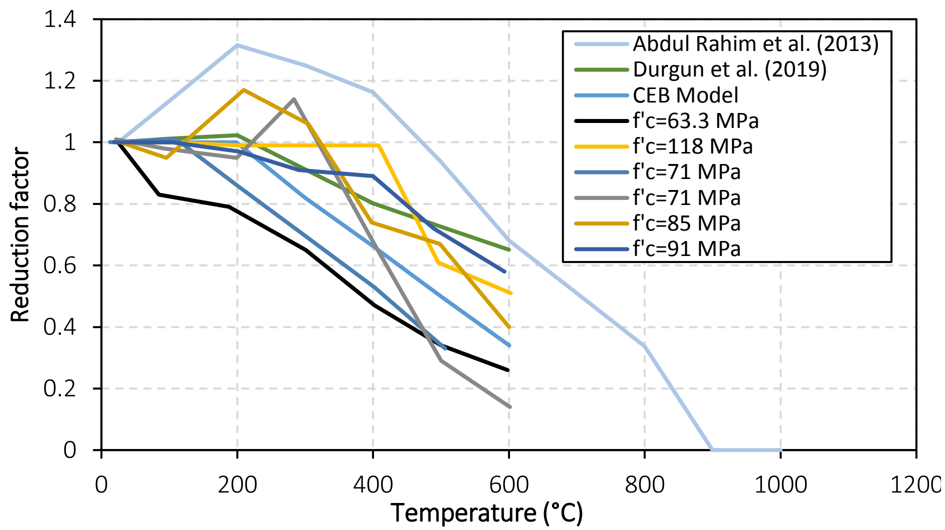


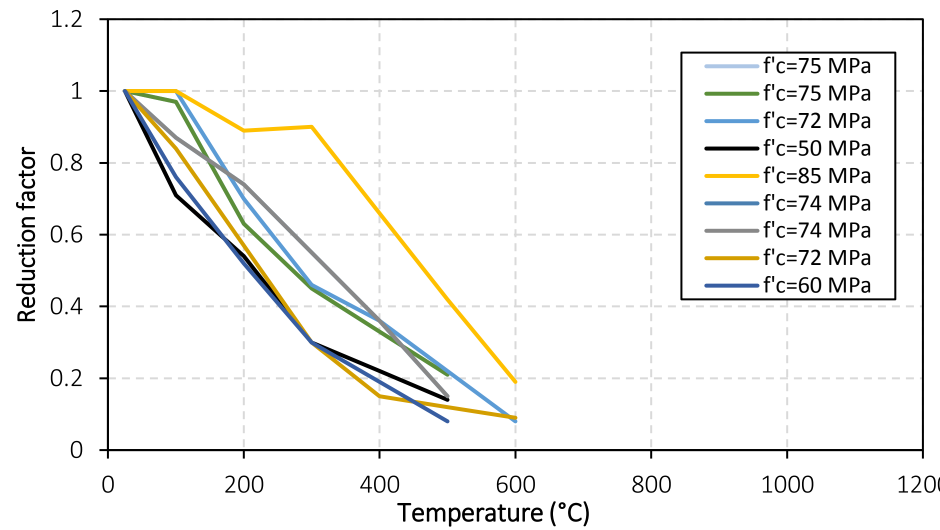
(a) Compressive strength of NSC



(b) Young's modulus of NSC (Naus, 2010)



(c) Compressive strength of HSC (Naus, 2010)



(d) Young's modulus of HSC (Naus, 2010)

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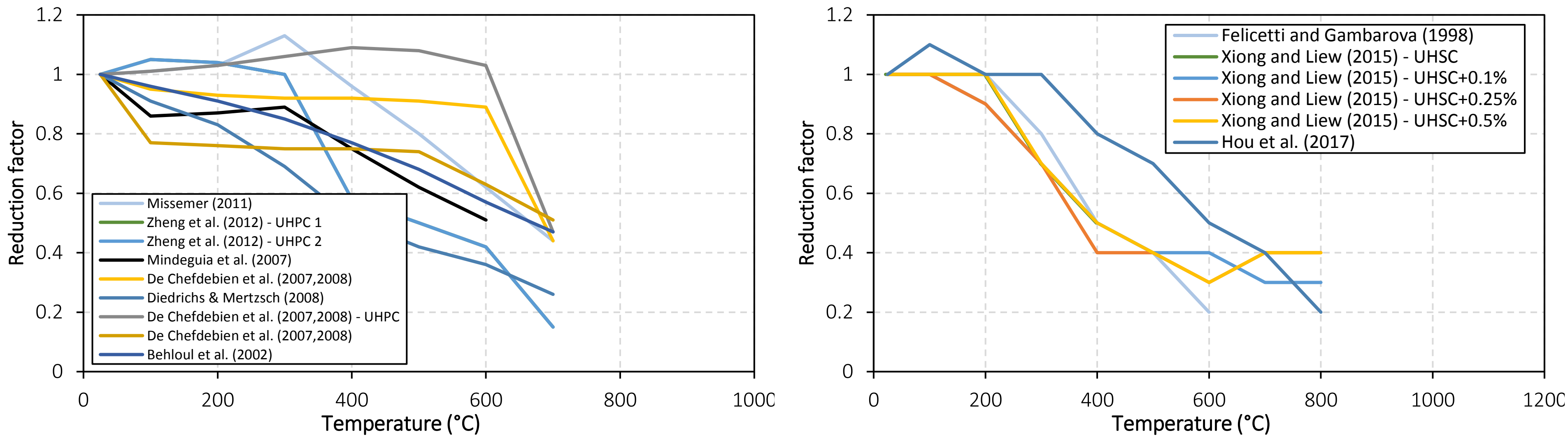

(e) Compressive strength of UHPC (f) Young's modulus of UHPC

Fig. 1 Residual properties of concrete derivatives

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In the case of metallics (MS, HSS, CFS, SS), Fig. 2 shows that the outcome of residual tests on these materials also show a scatter. However, this variation is of a much narrower range than that in concretes. This can be attributed to the consistency in composition and microstructure of these materials as opposed to that in concretes. In this particular case, Fig. 2 shows that the variation in yield strength in most metallics starts to become apparent once exposure temperature exceeds 500-600°C range. Interestingly, the Young's modulus property seems to undergo minor losses, if at all in MS, CFS and SS; as opposed to HSS. More specifically, Wang et al. (2018) tested specimens made of HSS and reported how the yield strength and Young's modulus of elasticity reduce to around 64% and 84% at 900°C while another research group that share the same name, Wang et al. (2015), showed that yield strength and Young's modulus of elasticity of HSS reduce to about 73% and 95% at the same aforementioned temperature. Gishan et al. (2019) tested CFS and observed how the yield strength reduces to around 60% (of ambient value) and Young's modulus of elasticity to be 97% after exposed to 800°C, whereas tests carried out by Gunalan et al. (2014) seem to contradict these observations (by reporting that the same properties reduce to around 38% and 88%, respectively). Three research groups primarily tested residual properties of SS coupons: He et al. (2019), Wang et al. (2014) and Gao et al. (2018), and showed that the yield strength starts to drastically diminishes beyond 900°C.

The residual properties of fiber-reinforced composites (FRP) are also considered in this work. The two most commonly used FRP types; glass FRP (GFRP) and carbon FRP (CFRP) are examined. These two FRP-based materials are often used in strengthening applications wherein concrete structures are retrofitted in the aftermath of an extreme loading event (i.e. impact, earthquake) or due to changing occupancy type/increased loading levels (Alkhrdaji et al., 2007). The main properties of interest to fire assessment include tensile strength and Young's modulus of these FRPs (Naser et al., 2019). As expected, very limited amount of works attempted to explore the residual properties of these materials due to the combustible nature of FRP as well as resin/epoxy. It is commonly accepted that FRP composites often lose much of their mechanical properties at moderately high temperatures and hence tend to be replaced once exposed to fire (Firmo et al., 2015). However, for the sake of completeness, the depicted plots in Fig. 2 terminate at a temperature range of 400-600°C.

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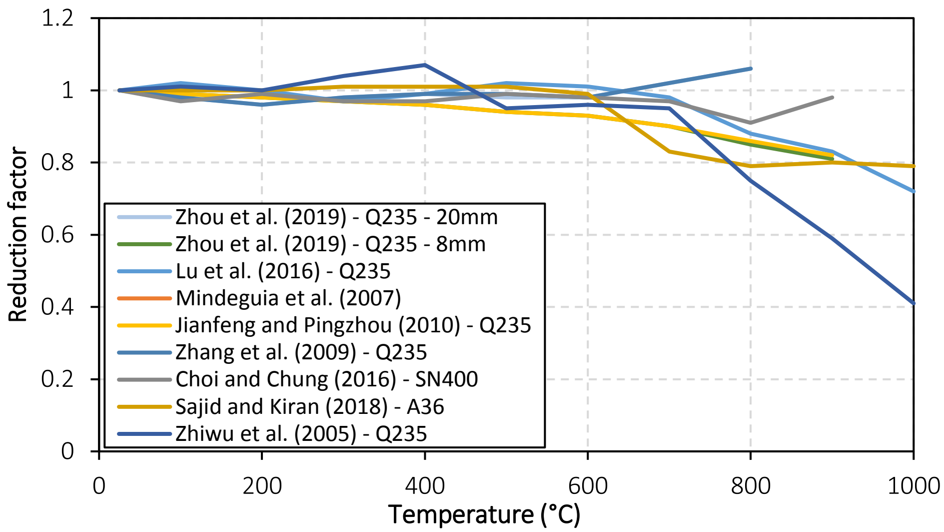
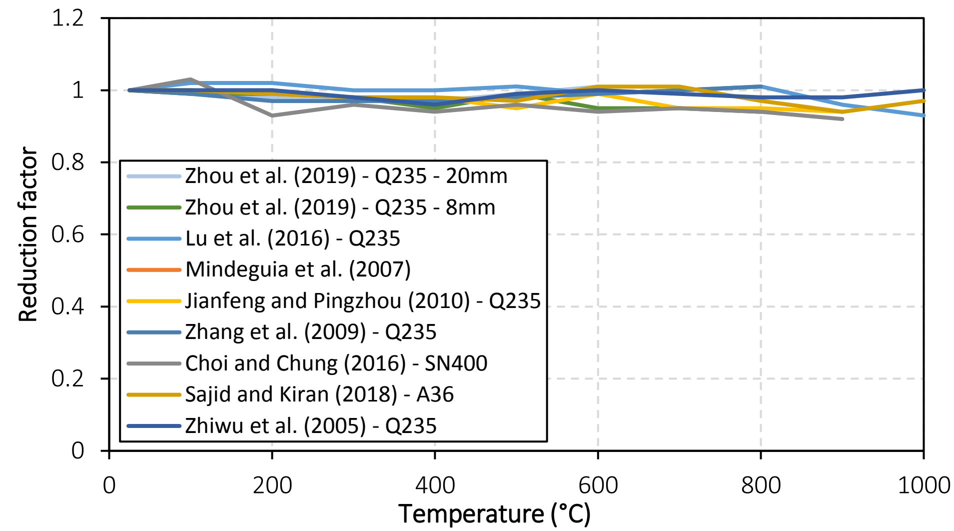
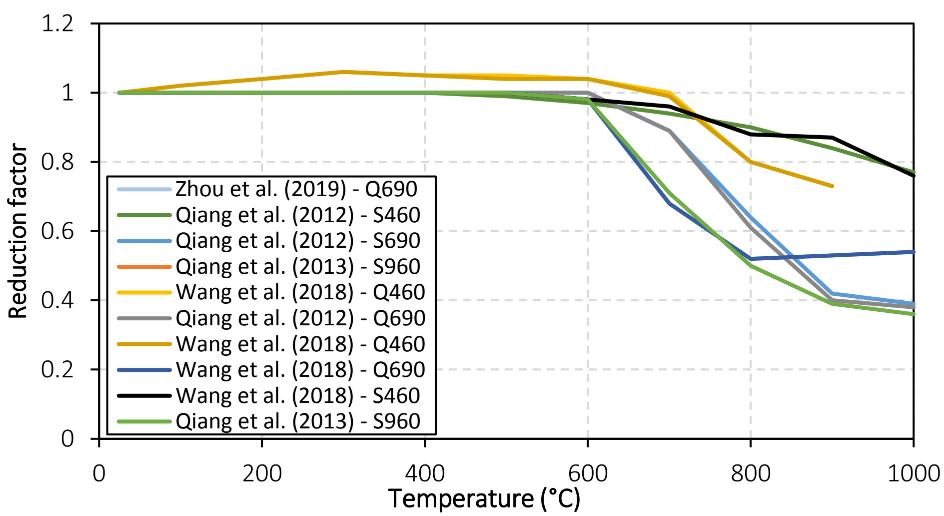


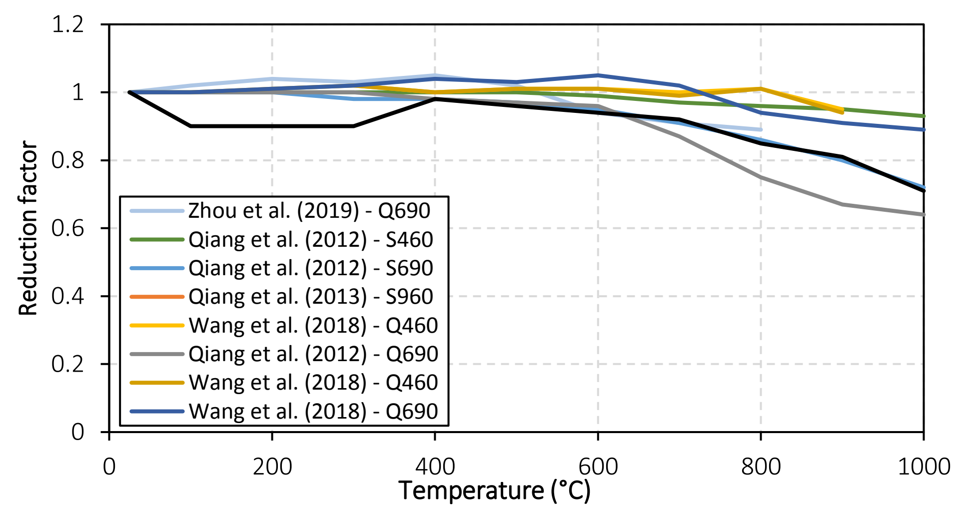
(a) Yield strength of mild steel (f_y < 450 MPa)



(b) Young's modulus of mild steel (f_y < 450 MPa)



(c) Yield strength of high strength steel (f_y > 450 MPa)



(d) Young's modulus of high strength steel (f_y > 450 MPa)

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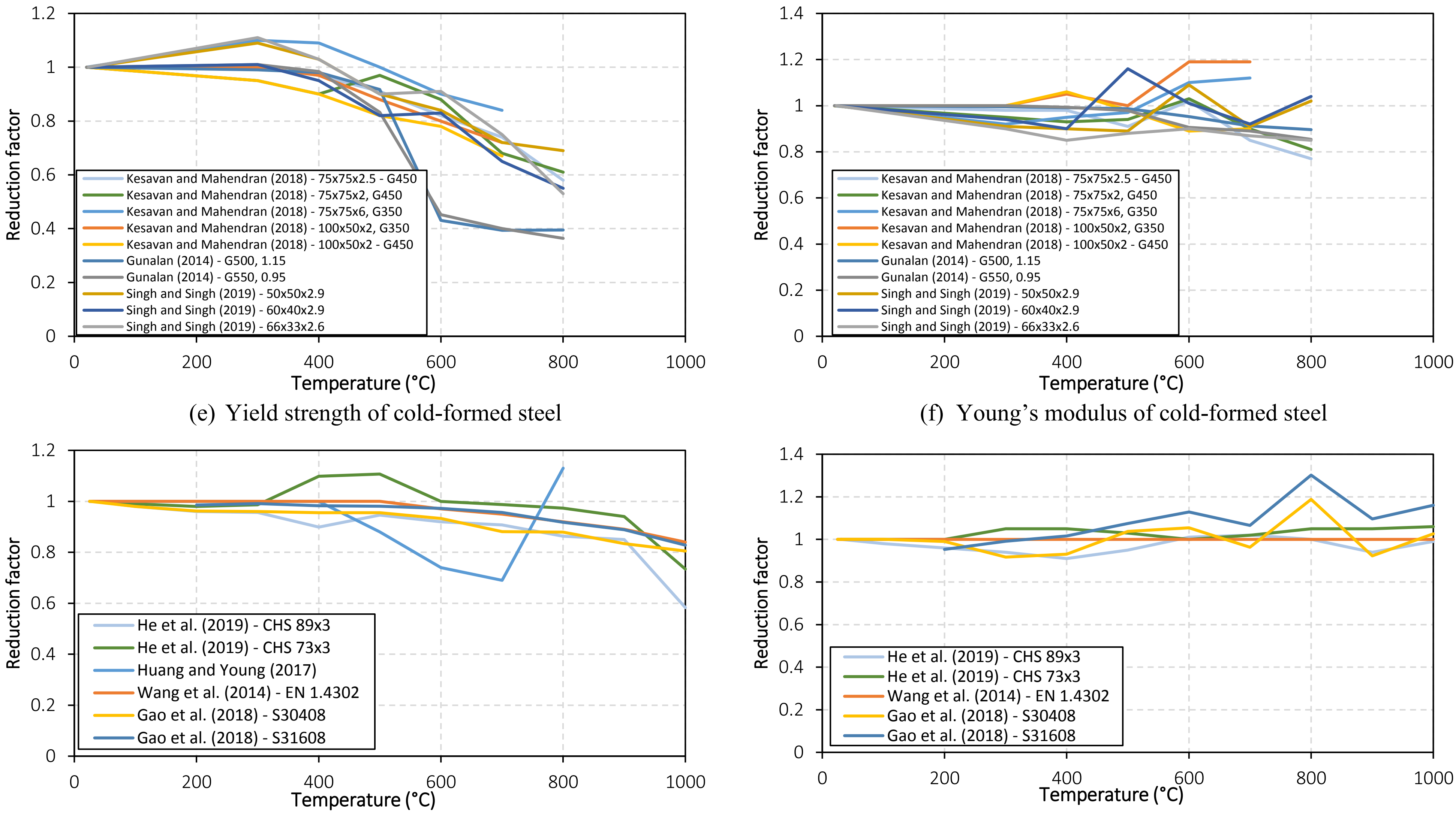

(e) Yield strength of cold-formed steel

(f) Young's modulus of cold-formed steel

(g) Yield strength of stainless steel

(h) Young's modulus of stainless steel

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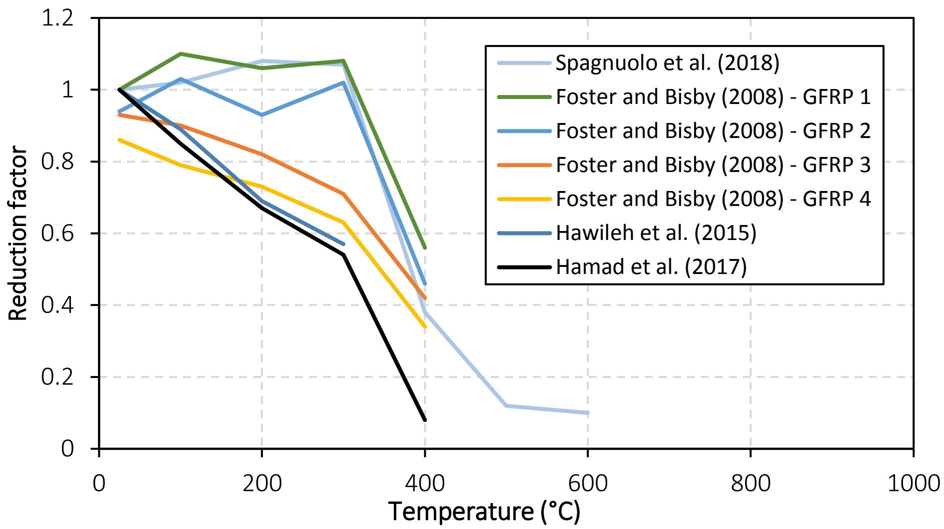
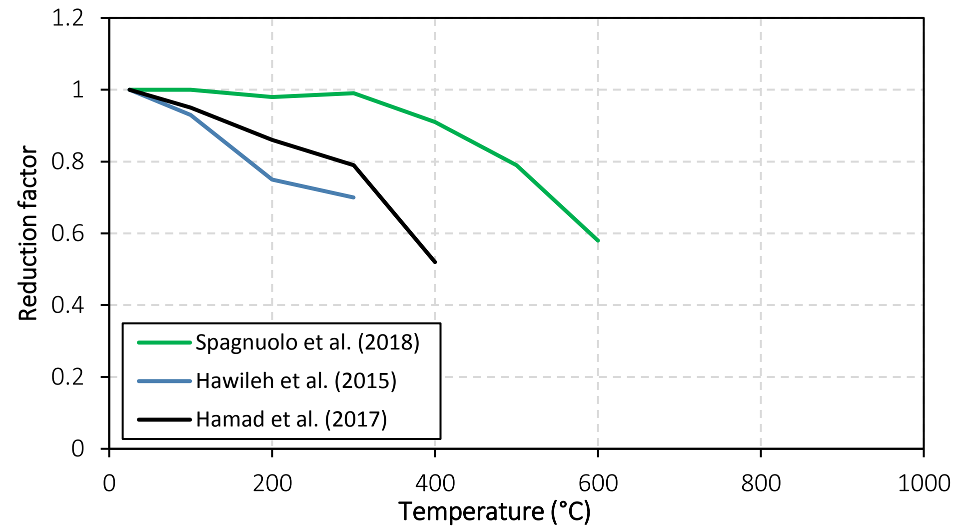
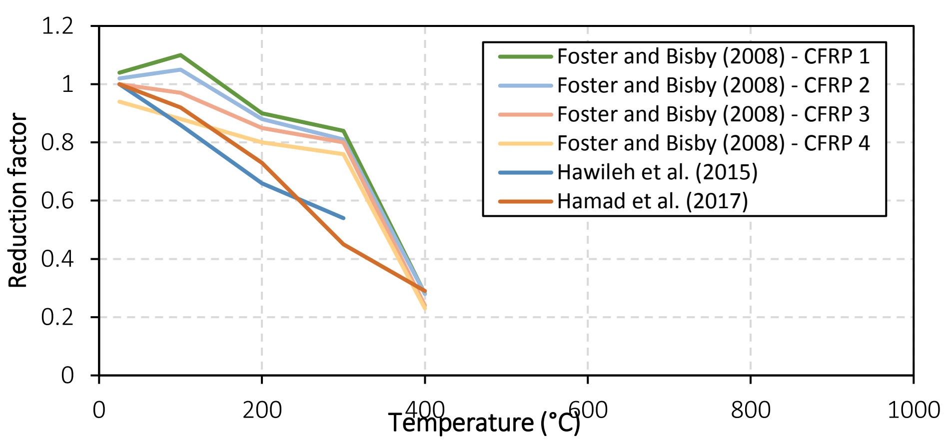


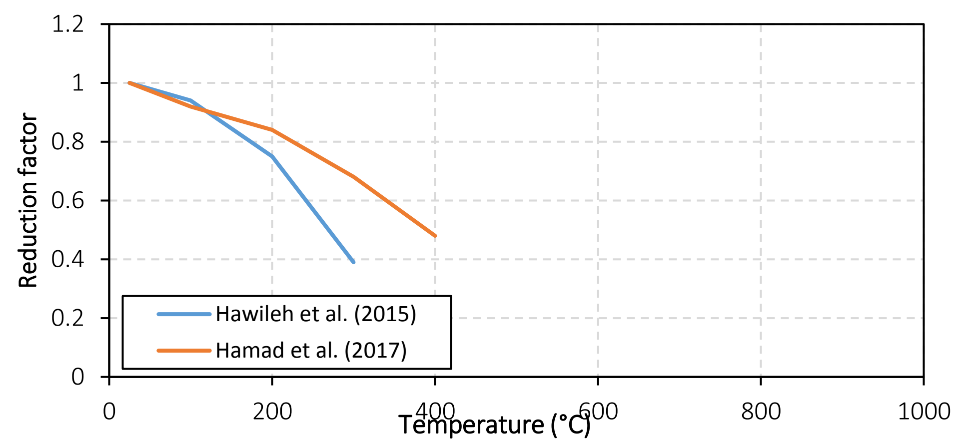
(i) Tensile strength of GFRP



(j) Young's modulus of GFRP



(k) Tensile strength of CFRP



(l) Young's modulus of CFRP

Fig. 2 Residual properties of steel and composite derivatives

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This critique clearly shows the wide scatter in measured residual properties for majority of construction materials. This scatter imposes technical questions and challenges to fire researchers and practitioners, especially those seeking to evaluate residual properties of construction materials or post-fire assessment of fire-damaged structures. This critique arises few key questions; for instance: Which material model to use in the process of assessing residual capacity of structures and structural members? How to ensure arriving at a uniform/consistent assessment between different practitioners or engineers in the aftermath of a fire incident given that there is not a clear guidance into which material model to use in such assessment process?

These questions could be answered by analyzing a collection of experimental measurements obtained from material tests that simulated varying post-fire conditions on construction materials. This analysis can be conveniently carried out using intelligent and modern solution techniques such as ANN and GA (Elsanadedy, 2019, Naser, 2018). These methods are described in detail in the following section.

3.0 Model development and description of machine learning techniques

Machine learning attempts to mimic the cognitive process that we possess. From this view, ML is a mere collection of algorithms; each developed with the intention of processing sets of data (or observations). In this work, such observations refer to the residual properties of construction materials that are measured at particular temperatures through material tests. These tests aim to replicate conditions that could occur in the aftermath of a fire event (i.e. cooling phase where maximum temperature drops back to ambient conditions). Of interest to this work is mechanical properties observed at temperature ranges between 25-1000°C, as this range covers the bulk of fire conditions most likely to occur in buildings and civil structures[7]. It should be stressed that the same approach presented herein can also be used to evaluate other property types (i.e. thermal, deformational, special etc.) and at other temperature ranges beyond the identified range herein.

In this paper, two ML techniques are used. These techniques include artificial neural network (ANN) and genetic algorithms (GA). For a start, ANN resembles the neural topology of the brain (see Fig. 3a). This network connects a number of layers; each containing neurons (processing units). The input layer, also the first layer in an ANN, receives input parameters governing a phenomenon (Abdalla and Hawileh, 2013). As discussed above, these inputs correspond to measured properties (viz. strength and modulus) at target cooling temperatures (i.e. 1000°C, .. 200°C, 100°C). This layer is then connected to ten successive[8] hidden layers through nonlinear activation functions such as Sigmoid, TanH etc. to allow universal approximation and/or be continuously differentiable (to permit gradient-based optimization etc.). The input data is then operated upon in an iterative and systematic learning process until the ANN manages to successfully captures the hidden patterns in the inputs responsible for realizing temperature-induced degradation in properties (Naser, 2019c). This learning process completes upon satisfying pre-defined performance metrics (i.e. mean square error, coefficient of determination R^2 etc.). The

[7]It is worth noting that in some infrastructure (bridges, tunnels etc.), fire temperatures can exceed this identified range due to different ventilation and fuel characteristics (i.e. open structures, hydrocarbon fuels etc.) (Kodur and Bhatt, 2016).

[8]The number of hidden layers was arrived at through a pre-examined sensitivity study.

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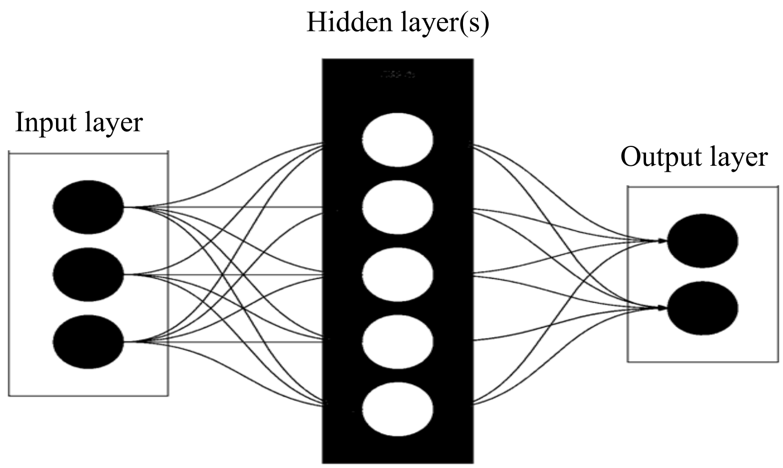
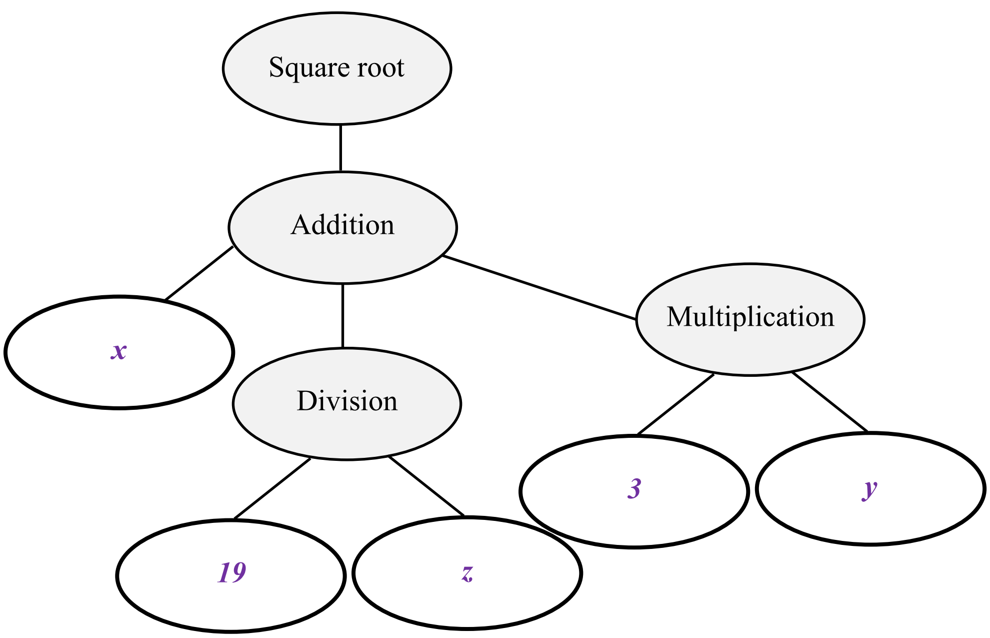
objective of the developed ANN is to attain a general representation that best exemplifies post-fire residual properties of construction materials. Such a network can be established using a deep learning tool in commercially available software such as Matlab or one that is customly developed. The outcome of the ANN analysis is then presented by the final (output) layer. The use of ANN has been duly noted in materials science applications.



(a)Layout of a typical artificial neural network



(b) A tree representation for Karva-expression: $\sqrt{\boldsymbol{x}+\frac{\mathbf{19}}{\boldsymbol{z}}+\mathbf{3}\boldsymbol{y}}$

Fig. 3 Details of genetic algorithm technique used in this study

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Genetic algorithms (GA) is the second ML technique to be employed herein. GA was originally developed by Koza (1992) as a tool to derive expressions to express a given phenomenon through a string of mathematical equations comprising of a tree-like data structure. The GA analysis starts with generating a random population of expression trees that consist of functions and terminals. A function may contain basic mathematical operations and functions (power, trigonometric etc.), while a terminal may contain arguments, constants and/or variables. The GA analysis often integrates genetic operations such as replication and crossover, to arrive at quick and optimal solutions. In these operations, GA-fit expressions are numerically manipulated and transformed into improved expressions with better fitness. Finally, the fittest solution is an expression tree that can be converted into a "Karva-expression" as can be seen in Fig. 3b. Similar to an ANN, a GA-expression is deemed fit once it satisfies predefined fitness metrics.

Overall, the presented hybrid approach applies ANN first to generate ANN-based properties at target temperatures by analyzing collected studies i.e. reduction factor for residual Young's modulus of HSS equals to 0.98 once cooled down from an exposure at 300°C and so on. Then, GA is applied to derive continuous relations that can represent variation in residual material properties post exposure to fire conditions. Thus, the values attained from ANN at specific temperatures (1000°C, .. 200°C, 100°C) are input into GA to derive a coherent expression. This approach is depicted in Fig. 4 and has been thoroughly examined and validated in parallel works (Naser, 2019a; c).

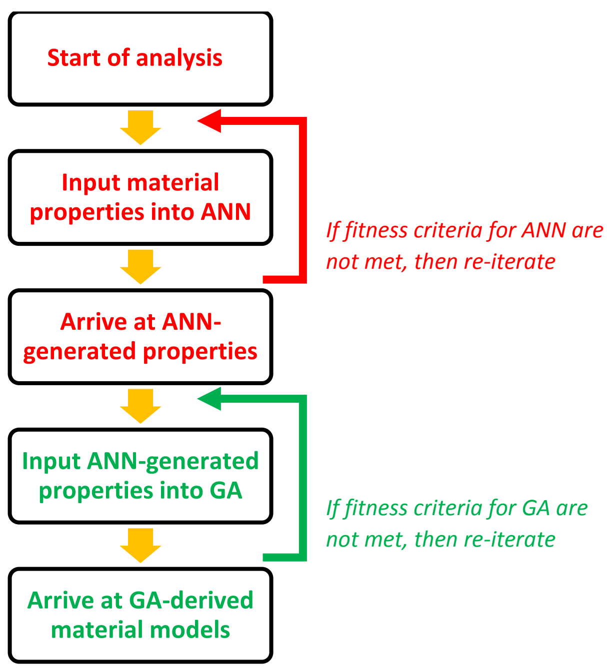

Fig. 4 Methodology followed in this study

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4.0 Performance and validation of derived material models

All compiled observations (i.e. measured properties or codal-adopted models i.e. CEB, Eurocodes) as depicted in Figs. 1-2 were randomly shuffled and then input into the developed ANN to initiate the neural network analysis. For each property, 70% of all data points were used in training the ANN and the remaining 30% were used to evaluate and test the ANN predictions. As discussed earlier, the properties investigated herein include compressive strength for concretes, yield strength for metallics, tensile strength for composites and Young's modulus property for all of these materials.

The outcome of this analysis is shown in Fig. 5. This figure shows how the ANN-predicted values at target temperatures precisely fit between collected observations. This can also be observed through examining fitness metrics i.e. coefficient of determination (R^2) and mean average error (MAE) listed in Table 1. As a result, one can safely presume that the ANN-generated predictions can be used to derive expressions for residual material models using GA. These expressions, together with their performance metric (R^2), are listed in Table 2.

Coefficient of determination (R^2):

$$R^2 = 1 - \sum_{i=1}^{n}(P_i - A_i)^2 \,/\, \sum_{i=1}^{n}(A_i - A_{mean})^2 \qquad \text{Eq. 1}$$

where *P* and *A* are predicted and actual values, respectively.

Mean average error (MAE):

$$MAE = \frac{\sum_{i=1}^{n}|E_i|}{n} \qquad \text{Eq. 2}$$

where *E* is the error between predicted and actual values for a particular observation.

Table 1 Performance metrics obtained through ANN

Material	Property	R^2	*MAE*
Normal Strength Concrete (NSC)	Compressive strength	92.1	0.93
	Young's modulus	95.3	0.81
High Strength Concrete (HSC)	Compressive strength	93.1	0.09
	Young's modulus	95.5	1.02
Ultra-High Performance Concrete (UHPC)	Compressive strength	94.3	0.90
	Young's modulus	96.7	0.89
Mild Steel (MS)	Yield strength	95.6	0.95
	Young's modulus	94.8	1.06
High Strength Steel (HSS)	Yield strength	91.4	1.09
	Young's modulus	97.6	0.99
Cold Formed Steel (CFS)	Yield strength	93.3	0.95
	Young's modulus	98.7	0.87
Stainless Steel (SS)	Yield strength	97.4	1.01
	Young's modulus	96.5	1.09
Glass Fiber Reinforced Polymer (GFRP)	Tensile strength	97.3	1.03
	Young's modulus	98.6	0.95
Carbon Fiber Reinforced Polymer (CFRP)	Tensile strength	92.1	0.99
	Young's modulus	98.2	0.87

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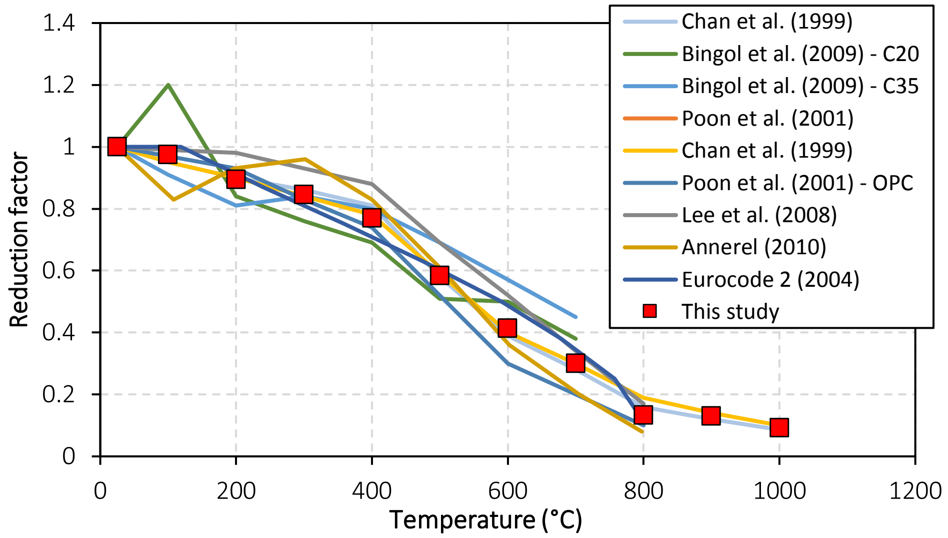
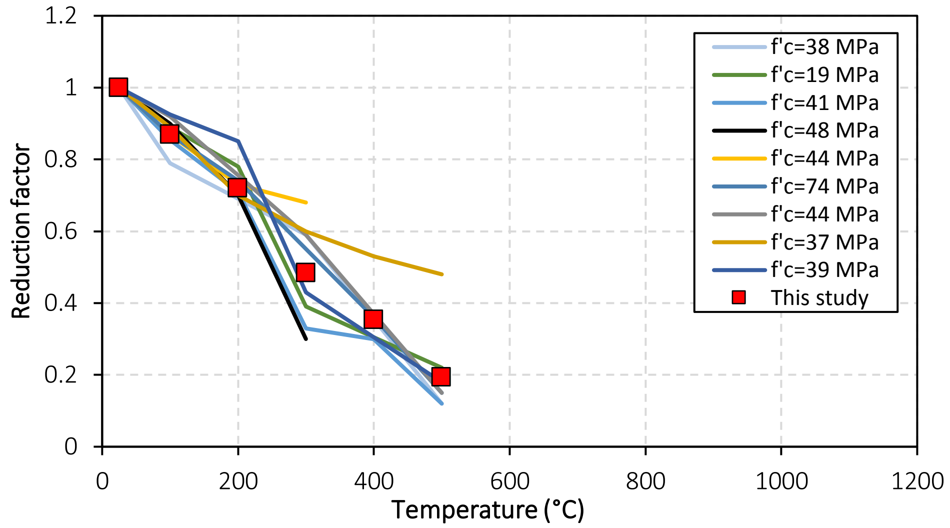


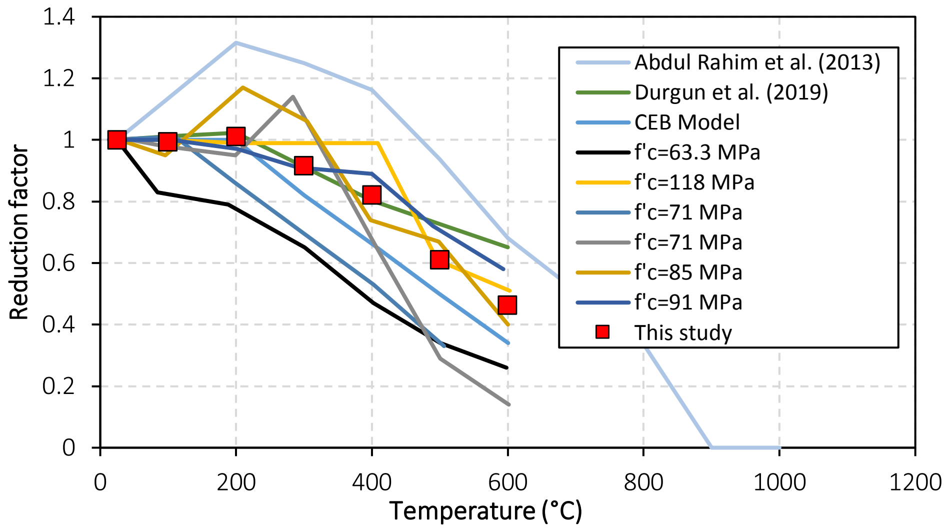
Temperature (°C)	$k_{NSC\_f'c}$
25	1.000
100	0.975
200	0.895
300	0.846
400	0.770
500	0.585
600	0.413
700	0.300
800	0.133
900	0.130
1000	0.093

(a) Compressive strength of NSC



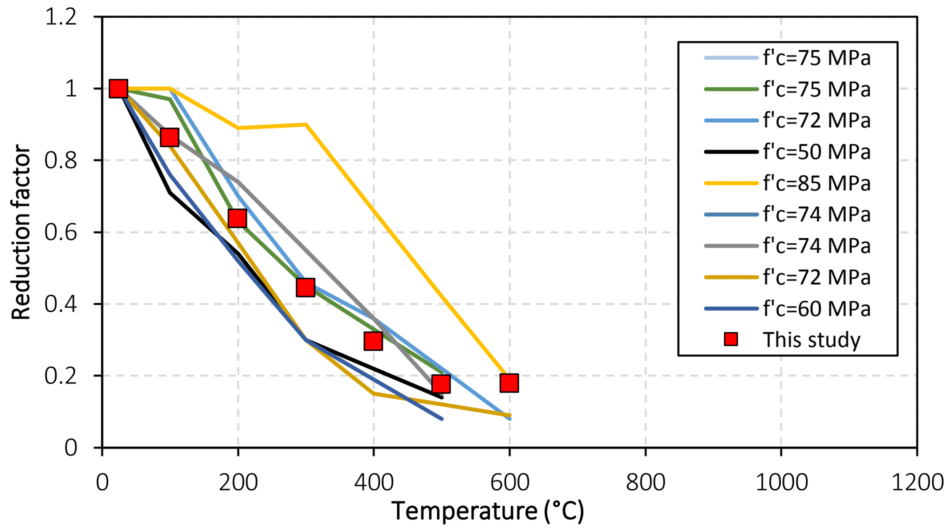
Temperature (°C)	k_{NSC_E}
25	1.000
100	0.870
200	0.722
300	0.484
400	0.355
500	0.194

(b) Young's modulus of NSC



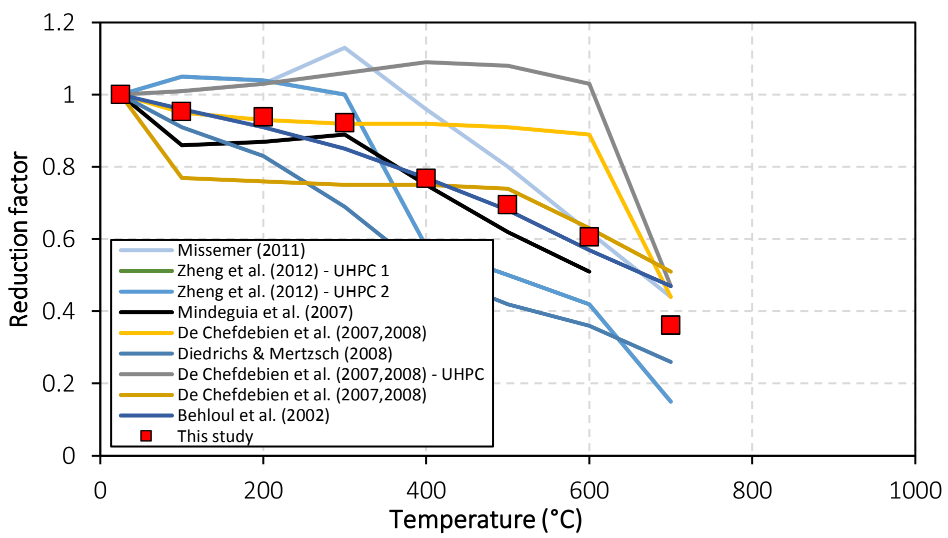
Temperature (°C)	$k_{HSC\_f'c}$
25	1.000
100	0.994
200	1.011
300	0.916
400	0.820
500	0.610
600	0.464

(c) Compressive strength of HSC



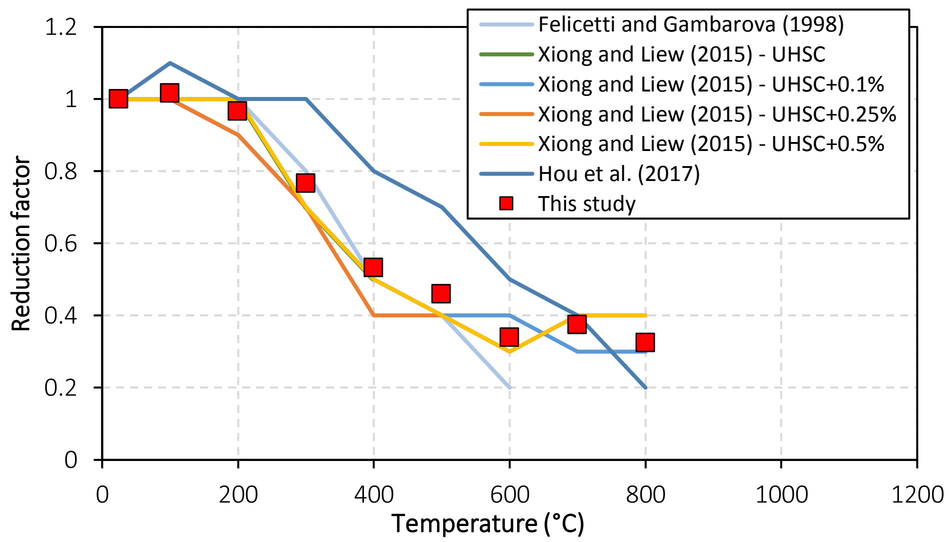
Temperature (°C)	$k_{HSC\_f'c}$
25	1.000
100	0.864
200	0.639
300	0.446
400	0.296
500	0.178
600	0.180

(d) Young's modulus of HSC



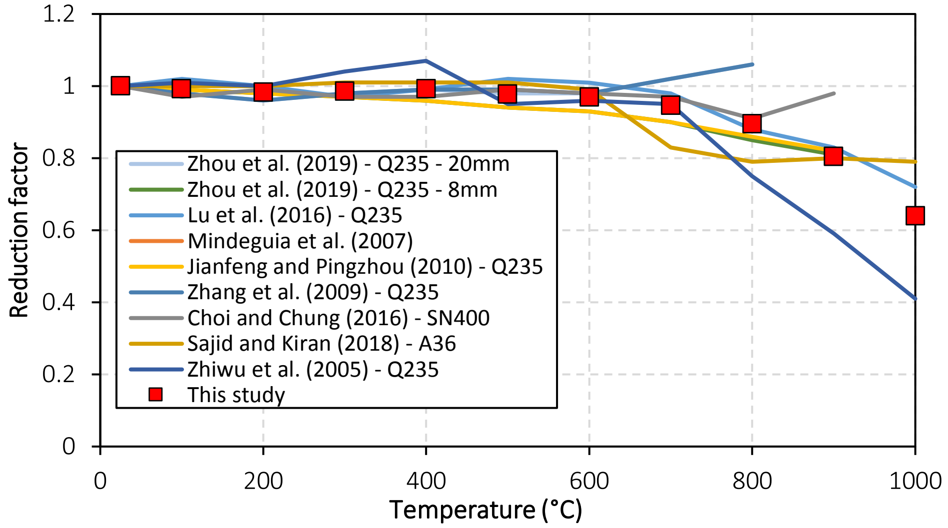
Temperature (°C)	$K_{UHPC\_f'c}$
25	1.000
100	0.952
200	0.938
300	0.921
400	0.768
500	0.694
600	0.606
700	0.361

(e) Compressive strength of UHPC



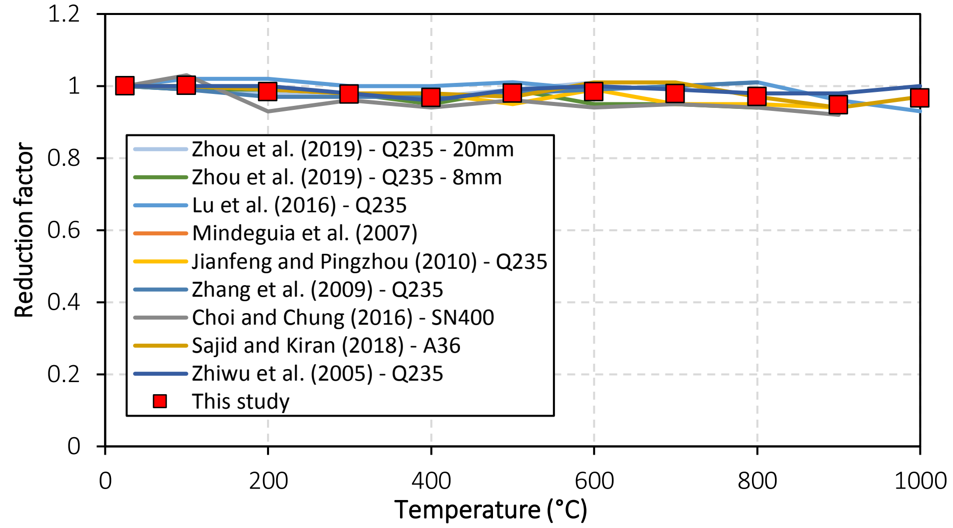
Temperature (°C)	$K_{UHPC\_f'c}$
25	1.000
100	1.017
200	0.967
300	0.767
400	0.533
500	0.460
600	0.340
700	0.375
800	0.325

(f) Young's modulus of UHPC



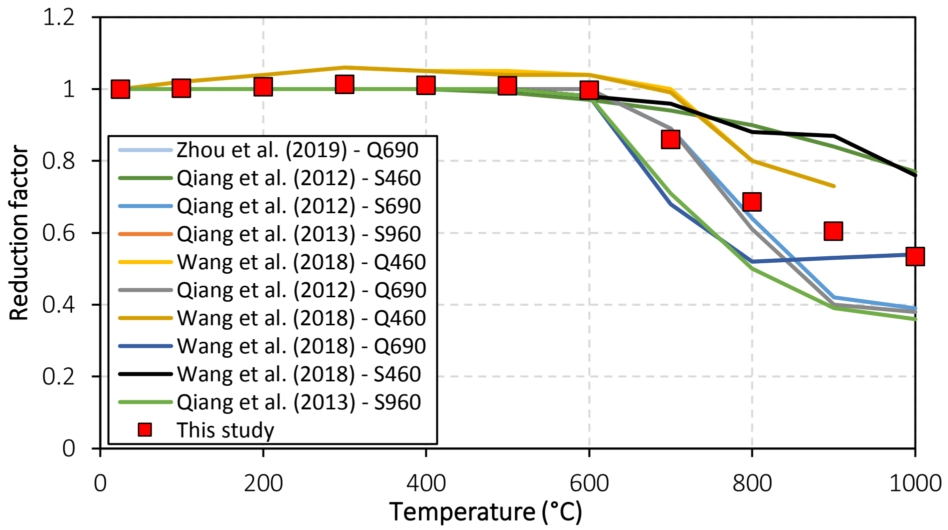
Temperature (℃)	K_{MS_fy}
25	1.000
100	0.993
200	0.984
300	0.986
400	0.993
500	0.978
600	0.970
700	0.946
800	0.895
900	0.805
1000	0.640

(g) Yield strength of mild steel (f_y < 450 MPa)



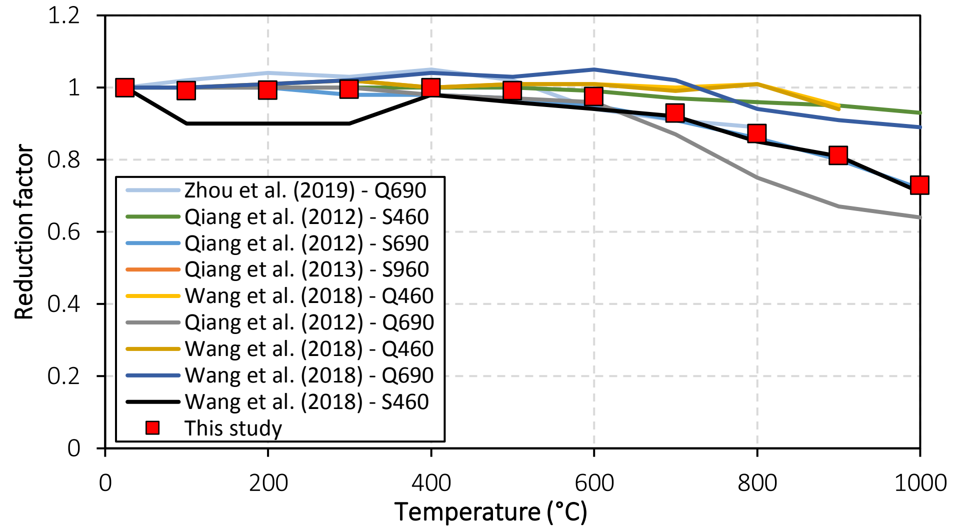
Temperature (℃)	K_{MS_fy}
25	1.000
100	1.003
200	0.984
300	0.978
400	0.969
500	0.980
600	0.985
700	0.979
800	0.971
900	0.948
1000	0.967

(h) Young's modulus of mild steel (f_y < 450 MPa)



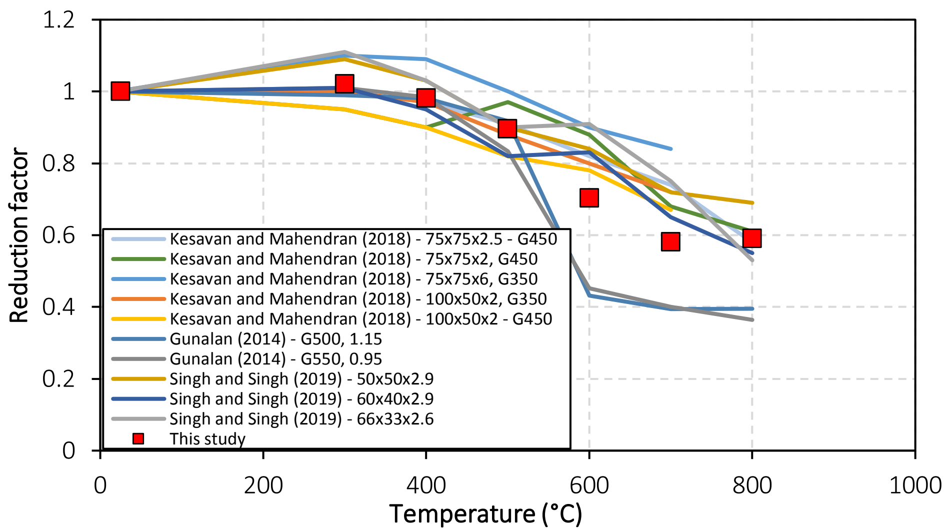
Temperature (℃)	$k_{HSS, fy}$
25	1.000
100	1.003
200	1.006
300	1.013
400	1.011
500	1.009
600	0.997
700	0.860
800	0.686
900	0.604
1000	0.534

(i) Yield strength of high strength steel (f_y > 450 MPa)



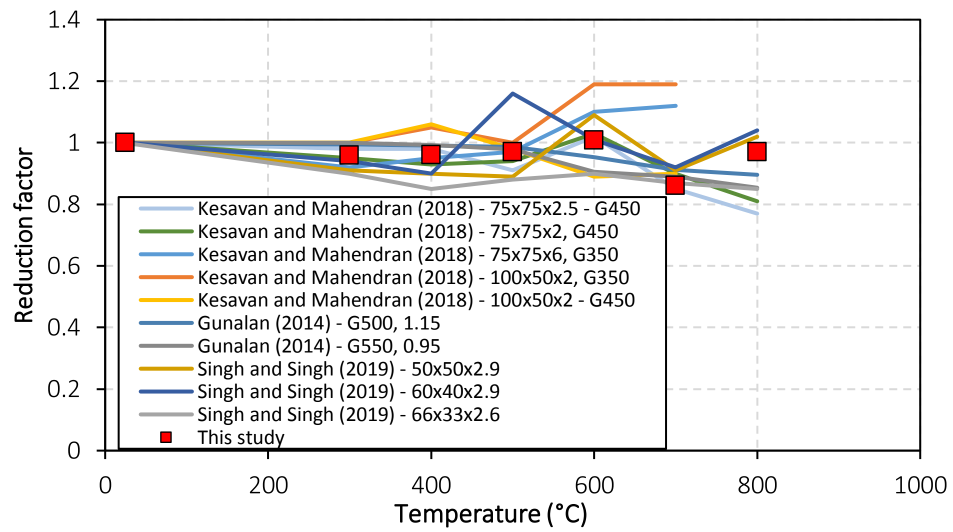
Temperature (℃)	$k_{HSS,E}$
25	1.000
100	0.991
200	0.993
300	0.995
400	0.999
500	0.991
600	0.975
700	0.929
800	0.873
900	0.812
1000	0.730

(j) Young's modulus of high strength steel (f_y > 450 MPa)



Temperature (℃)	$k_{cfs, fy}$
25	1.000
100	1.000
200	1.000
300	1.023
400	0.982
500	0.894
600	0.759
700	0.699
800	0.581

(k) Yield strength of cold-formed steel



Temperature (℃)	$k_{cfs, E}$
25	1
100	1
200	0.98
300	0.96
400	0.96
500	0.97
600	1.009
700	0.946
800	0.891

(l) Young's modulus of cold-formed steel

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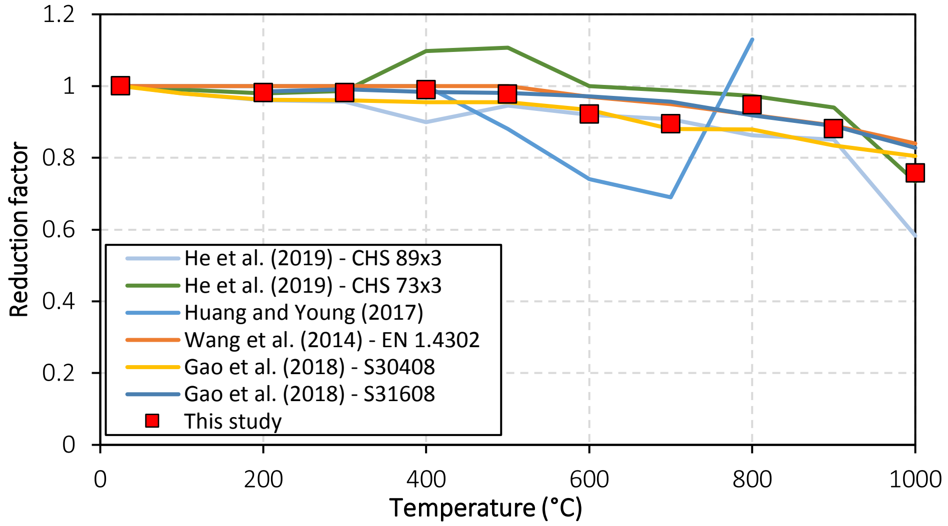
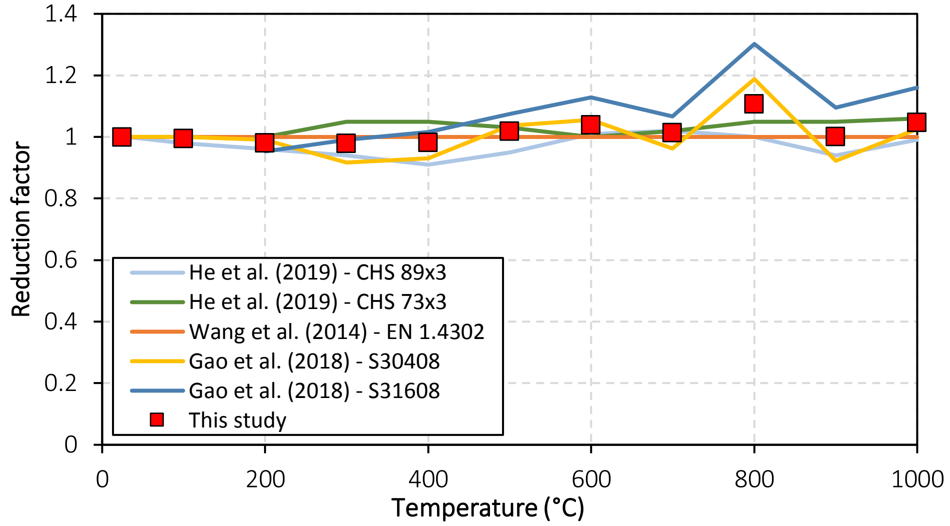


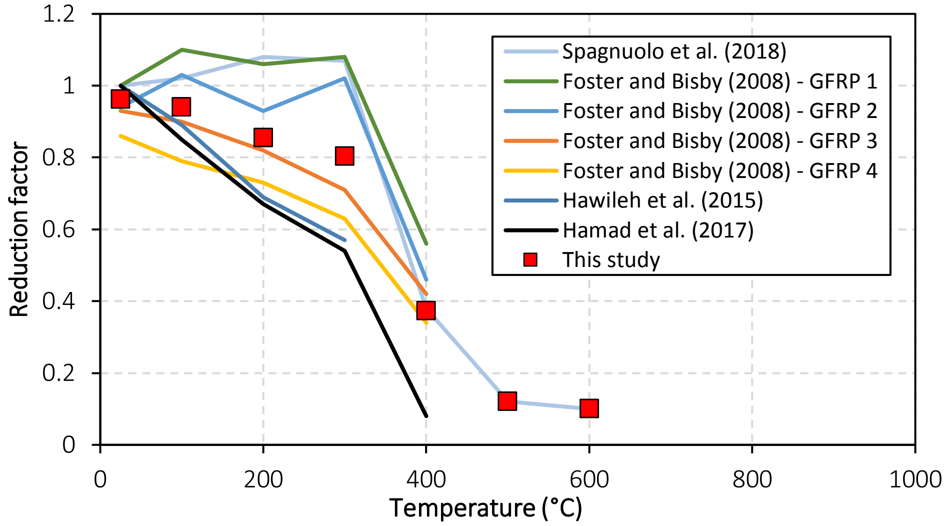
Temperature (°C)	$k_{SS\_f'c}$
25	1.000
100	1.000
200	0.981
300	0.982
400	0.989
500	0.978
600	0.923
700	0.895
800	0.947
900	0.881
1000	0.758

(m) Yield strength of stainless steel



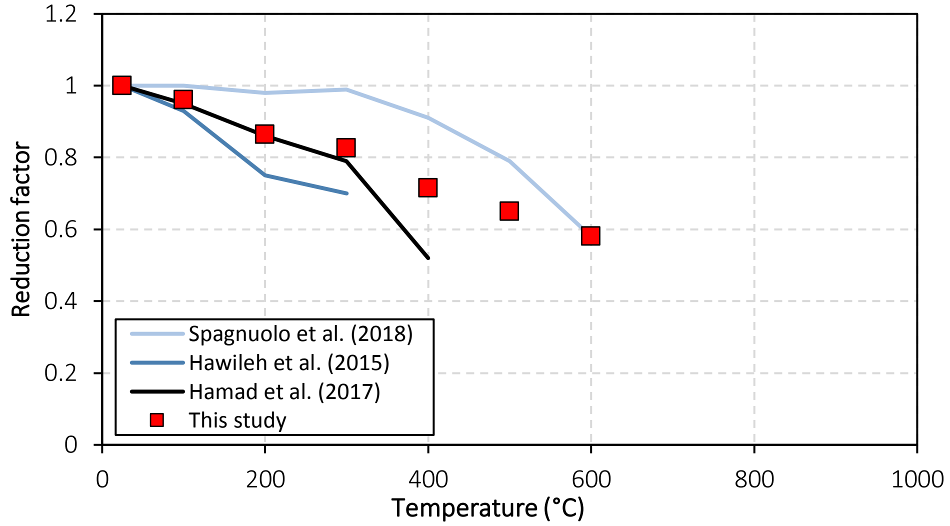
Temperature (°C)	$k_{SS\_f'c}$
25	1.000
100	0.995
200	0.981
300	0.980
400	0.981
500	1.018
600	1.039
700	1.014
800	1.108
900	1.002
1000	1.047

(n) Young's modulus of stainless steel



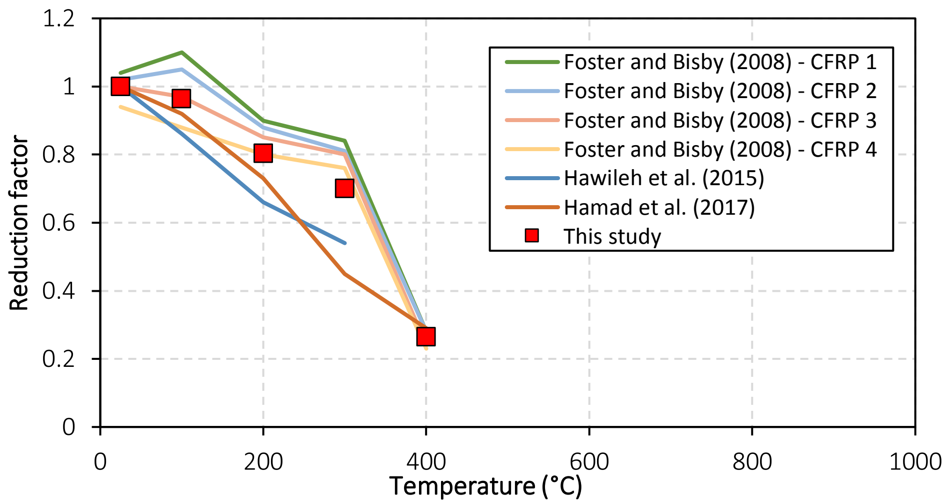
Temperature (°C)	$k_{GFRP,ft}$
25	0.961
100	0.940
200	0.854
300	0.803
400	0.373
500	0.120
600	0.100

(o) Tensile strength of GFRP



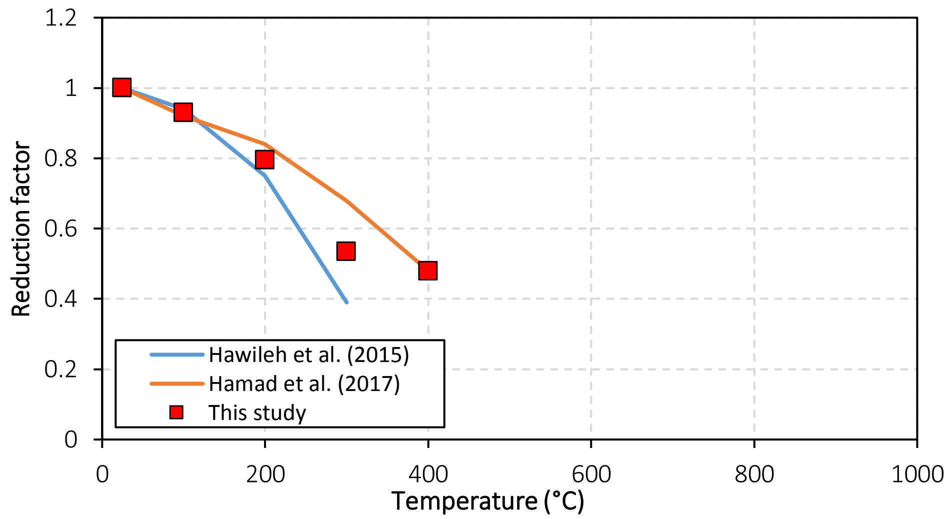
Temperature (°C)	$k_{GFRP,E}$
25	1.000
100	0.960
200	0.863
300	0.827
400	0.715
500	0.650
600	0.580

(p) Young's modulus of GFRP



Temperature (°C)	$k_{CFRP,ft}$
25	1.000
100	0.963
200	0.803
300	0.700
400	0.264

(q) Tensile strength of CFRP



Temperature (°C)	$k_{CFRP,E}$
25	1.000
100	0.930
200	0.795
300	0.535
400	0.480

(r) Young's modulus of CFRP

Fig. 5 Comparison between ML-derived and measured properties

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Table 2 GA-derived expressions of the reduction factors for residual mechanical properties of construction materials

Material	Property	Expression	R^2
NSC	Compressive strength	$k_{NSC\_f_c'} = 1.0 + 3.15e^{-12}T^4 + 4.99e^{-8}T^2\,sin(0.854T) - 0.000271T - 3.75e^{-9}T^3$	98.8
	Young's modulus	$k_{NSC\_E} = 1.01 + 5.33e^{-9}T^3 + 0.0238\,sin(0.791T) - 0.000946T - 3.99e^{-6}T^2$	99.1
HSC	Compressive strength	$k_{HSC\_f_c'} = 0.899 + 0.00114T + \frac{1.85}{T} + 2.68e^{-43}T^{15} - 3.47e^{-6}T^2$	99.7
	Young's modulus	$k_{HSC\_E} = 4.1e^{-7}T^2 + 2.69e^{-12}T^4 + 540\,atan(T^3) - 847 - 0.00235T$	99.6
UHPC	Compressive strength	$k_{UHPC\_f_c'} = 0.976 + 9.38e^{-17}T^6 - 9.37e^{-20}T^7 - 1.64e^{-11}T^4$	99.2
	Young's modulus	$k_{UHPC\_E} = \frac{49.4}{T} + 1.68\,log(T) + 8.2e^{-6}T^2 - 6.1 - 0.0122T - 2.43e^{-24}T^8$	98.5
MS	Yield strength	$k_{MS\_f_y} = 1.0 + 2.12e^{-7}T^2 - 0.000188T - 4.54e^{-16}T^5$	99.8
	Young's modulus	$k_{MS\_E} = 1.0 + 1.6e^{-9}T^3 + 2.55e^{-21}T^7 - 3.42e^{-18}T^6 - 7.7e^{-7}T^2$	96.1
HSS	Yield strength	$k_{HSS\_f_y} = 1.0 + 5.19e^{-9}T^3 + 3.09e^{-18}T^6 - 8.01e^{-12}T^4 - 7.35e^{-7}T^2$	99.1
	Young's modulus	$k_{HSS\_E} = 1.01 + 1.47e^{-6}T^2 + 9.35e^{-13}T^4 - 0.000281T - 2.4e^{-9}T^3$	99.7
CFS	Yield strength	$k_{cfs\_f_y} = 1.01 + 2.86e^{-6}T^2 + 1.63e^{-14}T^5 - 0.000503T - 1.76e^{-11}T^4$	99.2
	Young's modulus	$k_{cfs\_E} = 1.0 + asin\,(0.000104T\,asin(cos(T)^2) - 0.00012T - 5.11e^{-8}T^2$	97.8
SS	Yield strength	$k_{SS\_f_y} = 0.997 + 1.73e^{-5}T + 8.12e^{-8}T^2 sin\,(1.09T) - 1.79e^{-7}T^2$	99.4
	Young's modulus	$k_{SS\_E} = 0.995 + sinh(1.68e^{-7}T^2)\,sin\,(5.77 + T + cos(0.206T))$	95.7
GFRP	Tensile strength	$k_{GFRP\_f_t} = 0.949 + 6.93e^{-14}T^5 - 4.82e^{-11}T^4$	98.8
	Young's modulus	$k_{GFRP\_E} = 1.01 + 0.00059T - 2.47e^{-7}T^2 - 0.0208sin\,(-1.03T)$	99.7
CFRP	Tensile strength	$k_{CFRP\_f_t} = 0.964 + 0.00208T + 7.09e^{-8}T^3 - 3.88e^{-16}T^6 - 2.8e^{-5}T^2$	99.9
	Young's modulus	$k_{CFRP\_E} = 1.01 + 1.81e^{-16}T^6 - 0.000498T - 1.67e^{-8}T^3$	99.8

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5.0 Challenges and insights to future research needs

In order to assess the residual capacity of a structure after fire, knowledge on post fire material properties is essential. Due to the scatter nature of available material models, as well as complexity in collecting proper material samples taken from fire-damaged structure, a fire researcher or engineer may not be able to properly conduct such assessment. In order to overcome such challenges, this paper presents an approach to develop residual properties for commonly used construction materials by leveraging principles of ML. These models take into account variations in material composition and origin, occurrence of certain phenomenon (i.e. creep effects) to some extent, as well as differences arising from testing methods (e.g. set-ups, heating and loading rate, specimen sizes etc.) and hence are believed to be a first attempt to developing suitable representation of generalized material models (Chou et al., 2014, Naser, 2018, Ward et al., 2016).

It is worth noting that a collection of test observations was used in deriving each of the proposed material models. In the majority of cases[9], a minimum of 8 tests were used to derive such models and these tests were selected keeping two criteria in mind: 1) picked from works of different origins around the world, and 2) picked from studies conducted over the last two decades with emphasis on recent works as these closely reflect characteristics of commonly available construction materials. These criteria ensured that the derived models have a wide range of applications, while being representative of current advances in material sciences (Naser, 2019b, c).

In this process, few challenges were faced, and these are worthy of mentioning herein to emphasize transparency and guide future works towards research areas that need to be addressed. For a start, the decision of selecting a minimum of 8 tests was arbitrary and solely arises from the limited number of available tests that satisfy the above two selection criteria. While the derived models are believed to present an accurate representation of post-fire behavior of construction materials, these could potentially be improved by integrating additional test data points into the developed ML approach. These additional data points can be collected from existing tests or from those to be carried out in the future. We recommend hosting an open source and freely accessible database such that researchers around the world have the ability to freely access and update. We also recommend to update the derived expressions every 3-5 years (by including new data points) – in a similar manner to codal provisions which are being updated in a 2-5 year cycle. This will ensure maintaining properly derived material models, unlike the currently used models in European and American fire-related codes which have not been updated since their publication in early 1990s-2000s[10].

Another challenge faced during this work was the lack of uniformity in surveyed tests, whether with regard to proper documentation of material composition, fabrication process, testing set-up and equipment etc. For instance, a number of tests applied different peak temperatures. In one case, Gunalan (2014) tested CFS samples with exposure reaching to 800°C while the test data of Kesawan et al. (2018) have a peak temperature of 700°C. Due to such inconsistency, the number

[9]Expect those associated with GFRP and CFRP due to the scarcity of materials tests.

[10]Continuous updating of material models may not lead to significant changes between editions. This is still of importance to account for new advances in material sciences, fabrication, and use of new fillers, additives etc.

of input data samples at 800°C was less than at 700°C. A similar observation can also be seen by comparing the works of Hamad et al. (2017) and Hawileh et al. (2015) on residual properties of GFRP. While we cannot speculate into why some researchers chose to apply different heating rates and peak temperatures, one should keep in mind that items such as the limited availability and capabilities of testing facilities, objectives of carried out tests, availability of funding etc. could be possible challenging factors that may hinder fidelity of the proposed models (Kodur et al., 2012). Future researchers are invited to explore other ML techniques i.e. firefly algorithm (FA), and support vector machines (SVM) among others etc. which may lead to developing different design/assessment aids or charts or expressions that may better facilitate post-fire assessment of damaged structures (Erdem, 2017). In general, the predictive capability of ML approaches can be improved through collaborating with interdisciplinary researchers (i.e. material scientists, fire engineers and computer scientists). This collaborative effort could lead to realizing improved testing procedures that can mirror actual post fire conditions (by incorporating specific features such as the nature of temperature rise/cooling, type of fuel etc.). The outcome of these tests can then be used by software engineers to develop new algorithms or finetune existing ones such that they better fit the need of the fire/material science community.

6.0 Conclusions

This paper introduces an approach for deriving residual material models for a variety of construction materials. This approach leverages two machine learning (ML) techniques; namely, ANN and GA, to analyze measured test data points in order to develop generalized residual (post-fire) material models which can be utilized to provide researchers and practitioners of means to properly assess residual behavior of fire-damaged structures. In lieu of the above, these three items further summaries the outcome of this work:

- There is a lack of information on post-fire properties of construction materials (especially to high strength steels and composites). Future works are encouraged to examine properties of construction materials under a variety of simulated heating and cooling conditions.
- Machine learning can be a prominent tool to realize generalized material models.
- Given the unique nature of the proposed material models, these models could be used for post-fire investigations wherein the origins of construction materials are not fully disclosed or in the event where fire testing is not possible for samples/cores/coupons of such materials.
- Recent research efforts continue to call for developing modern representations of residual properties in order to facilitate post-fire investigations, ongoing standardization attempts and modernizing fire assessment methods.

7.0 Acknowledgment

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8.0 List of notations

Actual Values (A)
American Concrete Institute (ACI)

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American Institute of Steel Construction (AISC)
Artificial Neural Network (ANN)
Carbon Fiber Reinforced Polymer (CFRP)
Coefficient of Determination (R^2)
Cold Formed Steel (CFS)
Error between predicted and actual values for a particular observation (E)
Firefly Algorithm (FFA)
Genetic Algorithms (GA)
Glass Fiber Reinforced Polymer (GFRP)
High Strength Concrete (HSC)
High Strength Steel (HSS)
Machine Learning (ML)
Mean Average Error (MAE)
Mild Steel (MS)
Normal Strength Concrete (NSC)
Predicted Values (P)
Stainless Steel (SS)
Support Vector Machines (SVM)
Ultra-High Performance Concrete (UHPC)

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