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Performance-based design of RC beams using an equivalent standard fire

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Performance-Based Design of RC Beams Using an Equivalent Standard Fire

Abstract

The design of buildings for fire events is essential to ensure occupant safety. Supplementary to simple prescriptive methods, performance-based fire design can be applied to achieve a greater level of safety and flexibility in design. To make performance-based fire design more accessible, a time equivalent method can be used to approximate a given natural fire event using a single standard fire with a specific duration. Doing so, allows for natural fire events to be linked to the wealth of existing data from the standard fire scenario. In this paper, the use of an existing time equivalent method is reviewed and assessed for application in the performance-based design of reinforced concrete (RC) beams. The assessment is established by computationally developing the moment-curvature response of RC beam sections during fire exposure. The sectional response due to natural fire and time equivalent fire are compared. It is shown that the examined time equivalent method is able to predict the sectional response with suitable accuracy for performance-based design purposes.

Keywords: Standard Fire, Natural Fire, Reinforced Concrete, RC Beams, Performance-Based Design, Time Equivalent, Bending Moment-Axial Load Relationship

1. Introduction

In both Canada and the United States, buildings are primarily designed for fire events using prescriptive standards (NFC, 2015; NFPA 1, 2018), developed based on historic experience of real world and laboratory fires. Although these standards have been successful over the past decades in reducing fire related injuries, they provide minimal knowledge of structural integrity during the fire event, and as such, can only provide limited protection within the extent of the historic experience. To provide a better understanding for fire safety design, the most recent publication of ASCE-7 (2016) provides a framework for a performance-based approach. By implementing performance-based methodology in a fire safety analysis, structures can be designed using sound engineering principles to reduce construction costs and improve public safety.

1.1 Use of a Time Equivalent in Performance-Based Design

One of the first and more difficult steps in undertaking a performance-based fire design, lies in accurately defining the fire load applied to a structural element. Fire events are typically represented using a temperature-time relationship, depicting the change in a compartment's gas temperature over time (Fig. 1). Every fire event is different; however, a typical natural fire will follow the growth and decay profile identified in Fig. 1. The performance of a structural element varies greatly depending on a fire event's specific temperature-time relationship. For reinforced concrete (RC), it has been shown that a fire's heating rate, maximum temperature, cooling rate, and overall duration all influence strain development and material degradation (Mohamedbhai, 1986; Zhang et al., 2001). To simplify the complexity of natural fire events, the fire safety industry has defined a single standard fire, shown in Fig. 1 (ISO 834, 2014). The standard fire does not follow the typical profile of a natural fire event; instead, it was intended to describe a severe heating scenario that could be easily recreated using laboratory furnaces. Because the standard fire is not capable of representing a natural fire event, it lacks direct suitability for performance-based design purposes.

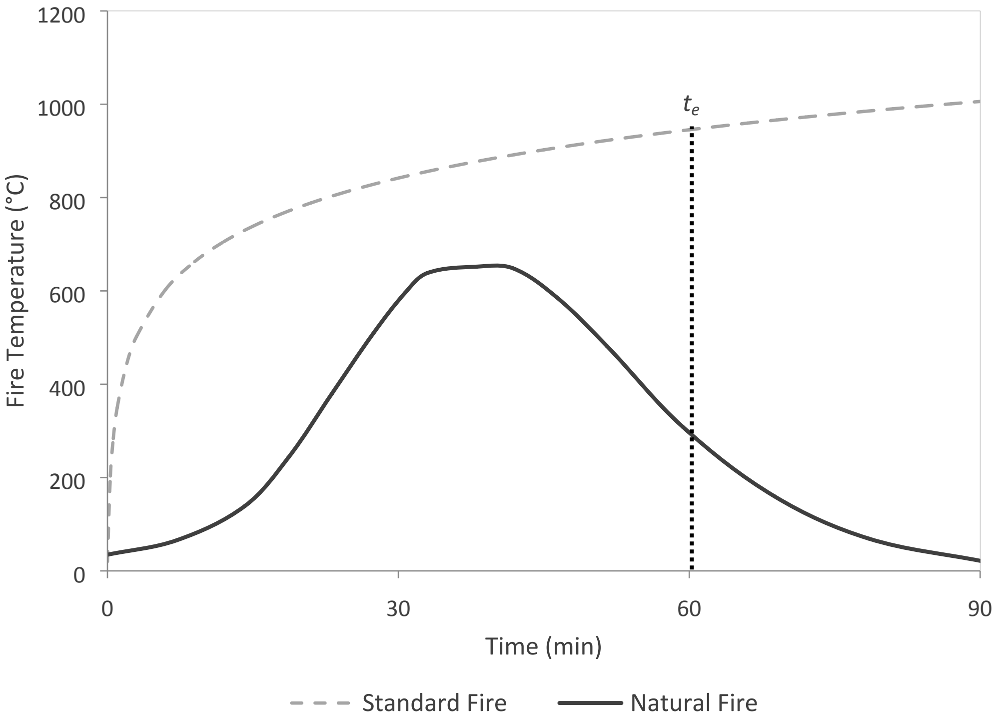


Fig. 1: Temperature-Time Relationship for Typical Natural and Standard Fire

A time equivalent (t_e), is a means by which the severity of a natural fire event can be approximated as a single standard fire duration. Using a time equivalent method, the wealth of existing data and material models developed with the standard fire, can be related to a natural fire event, and in turn, applied to a performance-based analysis. In a previous publication by the first two authors (Kuehnen and Youssef, 2019), a time equivalent (AITP t_e) was developed specifically for RC beams.

In this paper, the AITP t_e is first summarized, and then further evaluated in view of the flexural response of RC beams during natural fire exposure.

2. AITP Time Equivalent

During fire exposure, a typical RC beam undergoes heating from the two sides and lower face, resulting in an internal temperature gradient with hotter temperatures at the surface and cooler temperatures towards the core (Fig. 2a). To simplify an internal temperature gradient, the average internal temperature profile (AITP) can be calculated. This is achieved by dividing the section into a fine mesh and averaging the temperature across each horizontal mesh layer (Fig. 2b). The subsequent AITP of a section reflects the variation of the average temperature with depth. Application of AITP's in performance-based design has been proven in such publications as El-Fitiany et al. (2017) and El-Fitiany and Youssef (2009).

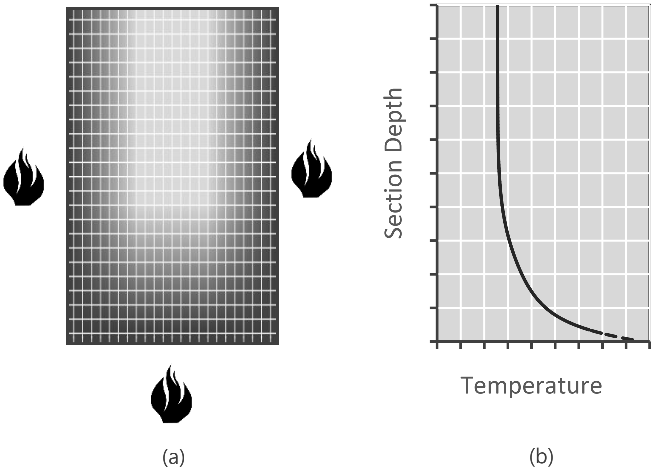


Fig. 2: Typical Section Internal Temperatures: (a) 2D Temperature Gradient and (b) AITP

The AITP t_e is defined as the duration of standard fire required to generate the equivalent AITP in an RC section as experienced by a selected natural fire (Kuehnen and Youssef, 2019). Equivalence is defined based on either mean or conservative criteria. A standard fire with a mean AITP t_e produces an internal temperature profile closely matching that of the natural fire. While a standard fire with a conservative AITP t_e results in a profile with equal or larger temperatures at every layer. A size adjustment factor (ψ_{size}) was also proposed in the original publication to account for the influence of variable beam width (b_c) and height (h_c) on the AITP t_e duration. The general equations to calculate the AITP t_e and ψ_{size} are provided in Equation 1, with coefficients and the valid ranges in Table 1 (Kuehnen and Youssef, 2019). To best characterize the general form of a natural fire, the equations were derived in terms of the maximum temperature (T_{max}), time of maximum temperature (t_{max}), and overall duration (t_{final}). For a worked example of the AITP t_e, refer to Kuehnen et al. (2019).

$$\begin{aligned} t_e = A + Bt_{max} + Ct_{final} + DT_{max} + Et_{max}^2 + Ft_{final}^2 + GT_{max}^2 \\ + Ht_{max}t_{final} + It_{max}T_{max} + Jt_{final}T_{max} \end{aligned} \tag{1a}$$

$$\psi_{size} = \begin{cases} 1.0 \begin{cases} for\ bc < 300\ m \\ for\ conservative\ t_e\ when\ T_{max} > 1150℃ \\ for\ conservative\ t_e\ when\ t_e > 180min \end{cases} \\ A + Bt_{max} + Ct_{final} + DT_{max} \\ \quad + b_c(E + Ft_{max} + Gt_{final} + HT_{max}) \geq 1.0 \end{cases} \tag{1b}$$

Table 1: Valid Ranges and Coefficients for Equation 1

		t_e (Eq. 1a)					ψ_{size} (Eq. 1b)	
		Mean	**Conservative**				**Mean**	**Conservative**
Valid Range	b_c (mm)	250	*250*				200 - 800	200 - 800
	h_c (mm)	500	*500*				300 - 800	300 - 800
	t_{max} (min)	15 - 115	*15 - 115*				15 - 115	15 - 115
	t_{final} (min)	20 - 240	*20 - 240*				20 - 240	20 - 240
	T_{max} (°C)	*350 – 1200*	*350 - 750*	*750 - 950*	*950 - 1100*	*1100 - 1200*	*350 – 1200* [1]	*350 – 1200*
Coefficients	A	8.124	8.685	2.370	566.30	4404.0	1.022	0.819
	B	-0.153	-0.0829	-0.0893	-0.465	-5.745	-2.57 x10^{-4}	3.78 x10^{-4}
	C	0.0384	0.0324	0.0446	1.188	1.039	2.69 x10^{-4}	-2.23 x10^{-4}
	D	-0.0431	-0.0428	-0.0186	-1.332	-8.177	-0.22 x10^{-4}	1.82 x10^{-4}
	E	-8.53 x10^{-4}	-4.74 x10^{-4}	-9.42 x10^{-4}	-20.00 x10^{-4}	-80.87 x10^{-4}	0.113	1.037
	F	-6.46 x10^{-4}	-4.16 x10^{-4}	-7.39 x10^{-4}	0.0	2.99 x10^{-4}	-8.23 x10^{-4}	-27.00 x10^{-4}
	G	0.50 x10^{-4}	0.66 x10^{-4}	0.35 x10^{-4}	7.95 x10^{-4}	38.36 x10^{-4}	14.01 x10^{-4}	27.15 x10^{-4}
	H	3.44 x10^{-4}	1.57 x10^{-4}	4.77 x10^{-4}	-3.07 x10^{-4}	-17.80 x10^{-4}	-1.93 x10^{-4}	-10.75 x10^{-4}
	I	6.55 x10^{-4}	5.33 x10^{-4}	5.40 x10^{-4}	12.05 x10^{-4}	69.36 x10^{-4}	---	---
	J	4.52 x10^{-4}	3.70 x10^{-4}	4.71 x10^{-4}	-9.00 x10^{-4}	-8.40 x10^{-4}	---	---

[1] Excluding T_{max} < 750 °C reached during t_{max} < 60 min

3. Moment-Curvature Assessment of the AITP t_e

Performance-based requirements are typically divided into serviceability and ultimate limit states, which can be measured using deflection and load capacity (Purkiss, 2007). In the case of RC beams, both of these requirements can be best represented by the sectional bending moment-curvature (M-φ) response. To evaluate the AITP t_e in the application of performance-based design, a study was undertaken to develop the fire exposed M-φ relationship for a variety of RC beam sections and a range of natural fires. In this section, the sectional analysis method, study parameters, and evaluated results are presented to demonstrate the suitability of the AITP t_e.

3.1 Sectional Analysis Method

A structural analysis program developed by El-Fitiany and Youssef (2009) was used to produce the M-φ response of beams during fire exposure. The program has three main steps: (1) determine the internal temperatures of the section, (2) evaluate the thermal strains at elevated temperature and (3) iteratively simulate an applied load to approximate the full sectional response. Section internal temperatures are calculated using the finite difference method (FDM) presented by Lie (1992). Three-sided fire exposure is applied to the RC section from the two sides and lower face. Concrete thermal strains (ε_T) are estimated using the equations provided by Youssef and Moftah (2007). Sectional analysis is then carried out iteratively to determine the M-φ relationship. The program makes the following assumptions: (1) plane sections remain plane during fire exposure, as previously validated up to 1200°C by El-Fitiany and Youssef (2011); (2) perfect bond exists between steel and concrete; (3) normal strength concrete (NSC) is used, and thus, explosive spalling can be ignored; (4) influence of concrete tensile cracks on heat flow is ignored; and (5) geometrical nonlinearity is not considered.

3.2 Study Methodology

For a given RC section, the M-φ response was calculated for both natural and standard fire exposure. The natural fire was assembled based on experimentally recorded temperature-time relationships and theoretical profiles developed using the Eurocode approach (EN 1991-1-2, 2002). The standard fire was applied following the ISO profile (ISO 834, 2014) for a given mean or conservative AITP t_e duration. Each cross-section was evaluated for three fire events: the design fire, the AITP mean standard fire, and the AITP conservative standard fire. Due to the impracticality of displaying the full M-φ diagram for a large range of design fires and cross-sections, three key responses are identified for comparison. They are: the maximum moment at elevated temperature (M_{rT}), the initial curvature at elevated temperature (φ_{iT}), and the initial stiffness at elevated temperature (EI_{iT}). These three responses are crucial to defining the M-φ relationship, and in turn, the serviceability and ultimate limit states needed for performance-based design.

3.3 Sample RC Sections and Fire Exposures

Seven rectangular sections were selected to examine the M-φ response. Table 2 displays the section properties. The studied parameters are: concrete strength (f'_c), section width (b_c), section height (h_c), tension reinforcement ratio (ρ_s), and aggregate type (*agg.*) of either siliceous (*sil.*) or calcareous (*cal.*). Fig. 3 exhibits general details of the studied cross-sections. At ambient conditions, the value of f'_c is specified as either 30 or 40 MPa, and the steel yield strength (F_y) is held constant at 400 MPa. Longitudinal steel area was equally split into 3 bars, spaced at 55 mm from center to concrete face. Thermal properties for normal strength concrete (NSC) with siliceous and calcareous aggregate were applied from Lie (1992). The consideration of compression reinforcement and stirrup confinement was neglected for simplicity.

Table 2: Parametric Study Beam Properties

Beam #	F_y	f_c'	b_c	h_c	ρ_s	agg.	Studied Parameter
	MPa	*MPa*	*mm*	*mm*	*%*	---	
B1	400	30	250	500	1.0	sil.	*p*
B2					1.5		*p*
B3					2.0		*p*
B4					1.0	cal.	agg.
B5		40			1.0	sil.	f_c'
B6		30	400	800	1.0		b_c, h_c
B7			600	800	1.0		b_c, h_c

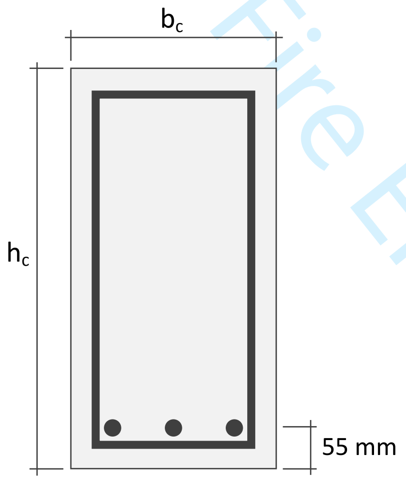


Fig. 3: Cross Section of Parametric Study RC Beam

Seven design fires were specified for the study (Fig. 4). The first five were developed using the Eurocode approach to demonstrate a range of possible natural fire events (EN 1991-1-2, 2002).

They can be broadly categorized as moderate, large, small, rapid hot, and long cool. The remaining two fires were taken from the experimental literature presented by Kirby et al. (1994) and Lennon (2014). The two experimental programs provide a good representation of typical natural fires that can occur in a concrete structure. The AITP t_e can be determined using Equation 1 based on the graphical interpretation of the fire profiles in Fig. 4.

In total, the study consists of 147 test cases using the seven cross-sections, seven design fires, seven AITP mean standard fires, and seven AITP conservative standard fires. It should be noted, that B6 and B7 possess a b_c greater than 350 mm, and therefore do not meet the condition of the mean ψ_{size} in the case of FR 4, when T_{max} is less than 600°C. These two non-valid cases were excluded from the study for the mean t_e.

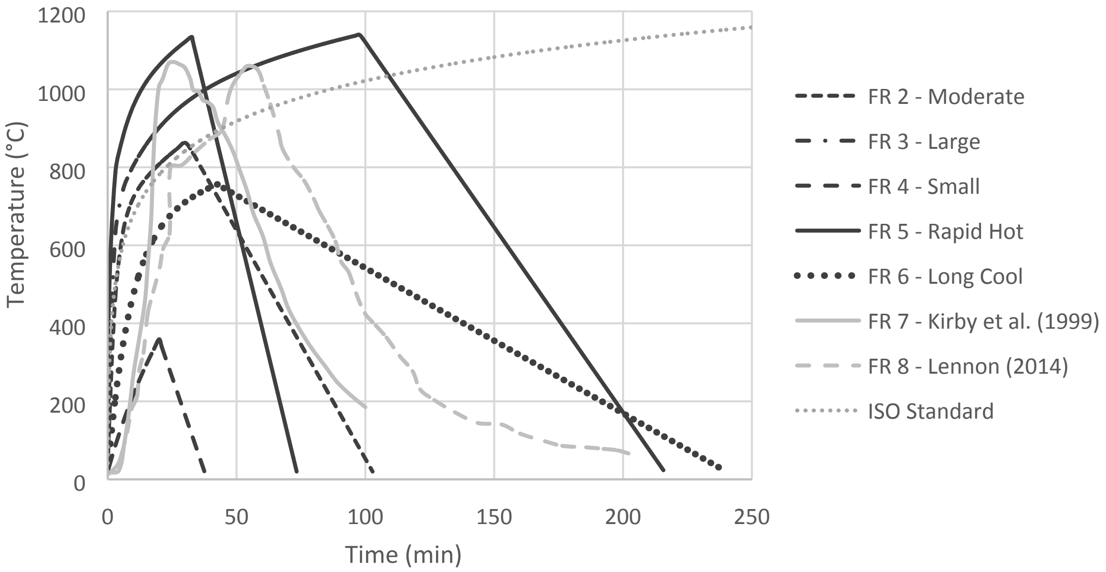
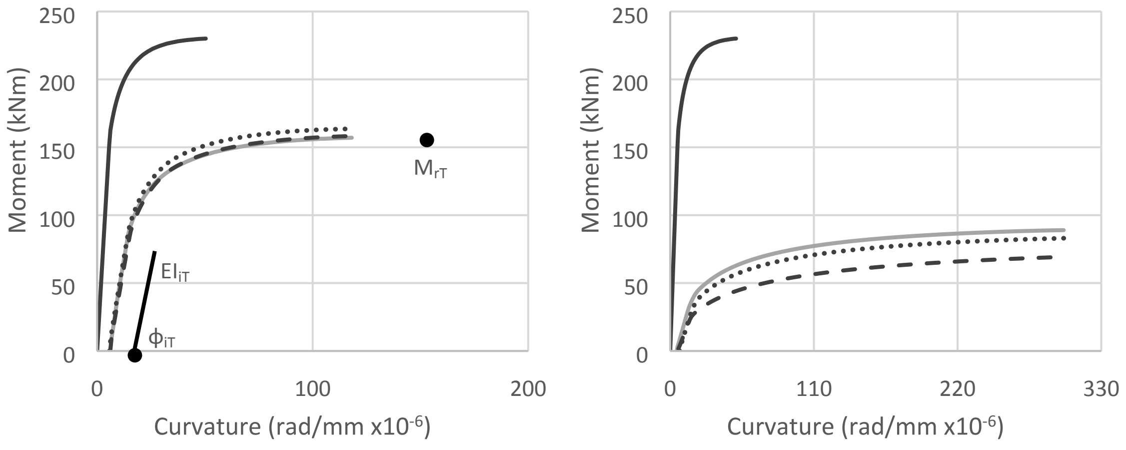


Fig. 4: Representative Design Fire Profiles

3.4 Mechanical Response Assessment

Figure 5 displays the full *M-φ* diagrams for B1 during the various fire exposure regimes. The ambient temperature profile is also provided as a baseline. All of the fire events led to the expected response of lowering the moment capacities and increasing the curvatures. The small fire (FR 4) resulted in only minimal internal temperatures within the section, and as such, virtually no visible change occurs to the *M-φ* diagram during fire exposure. For all seven fire events, the mean t_e presents a good fit with the design response. The highest deviation occurs for the large fire (FR 3), but the accuracy of the moment capacity remains at most within 6.7% of the actual. The conservative t_e produced a conservative profile, with lower moment capacity and larger curvatures for all seven design fires. For the rapid hot fire (FR 5), the conservative t_e is significantly longer in duration than the mean t_e, allowing it to capture the high surface temperatures that occur during rapid hot events. The *M-φ* response of FR 5 reflects this fact, showing a very conservative estimate for the conservative t_e. The experimental design fires of FR 7 and FR 8 likewise correlate well with the AIT t_e approximations.



(a) FR 2 - Medium

(b) FR 3 - Large

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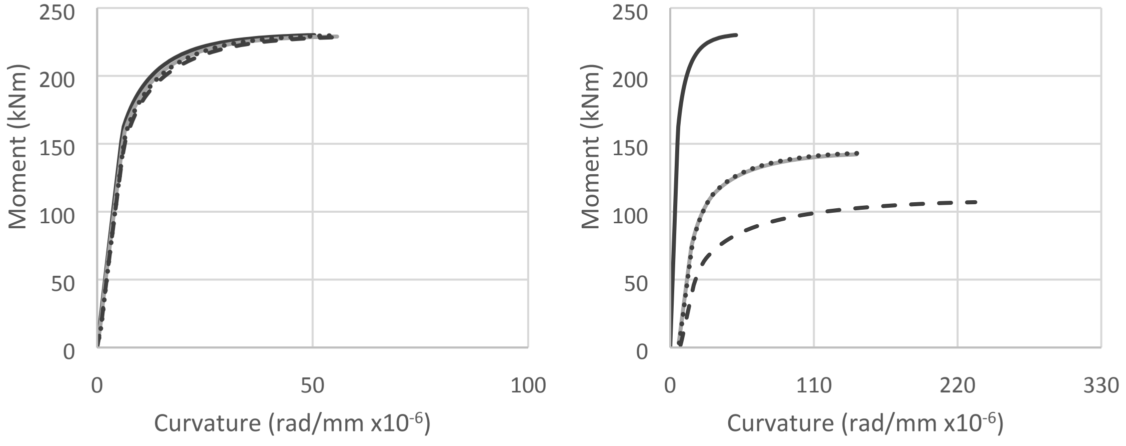
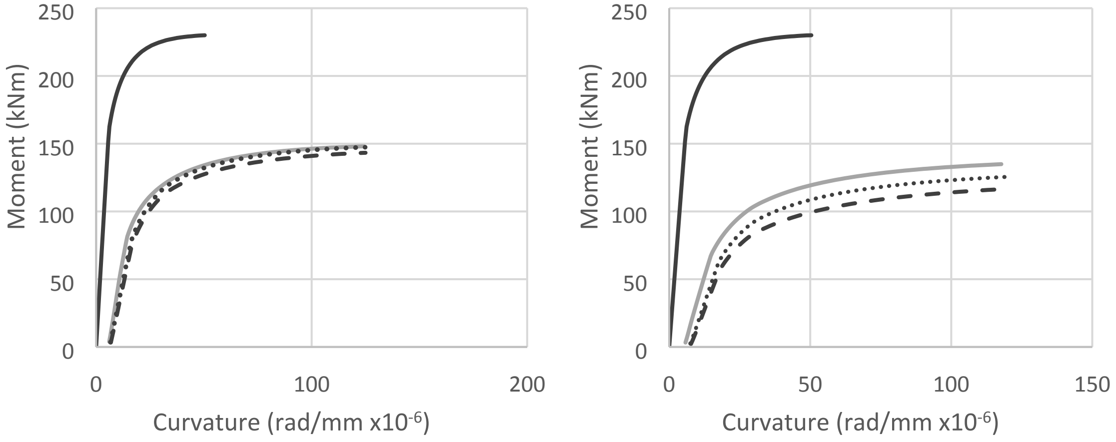


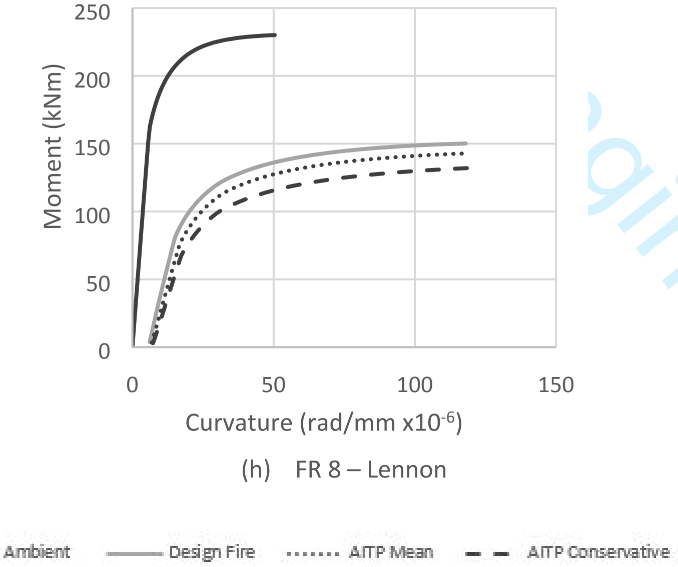
(c) FR 4 - Small

(d) FR 5 - Rapid Hot



(e) FR 6 – Long Cool

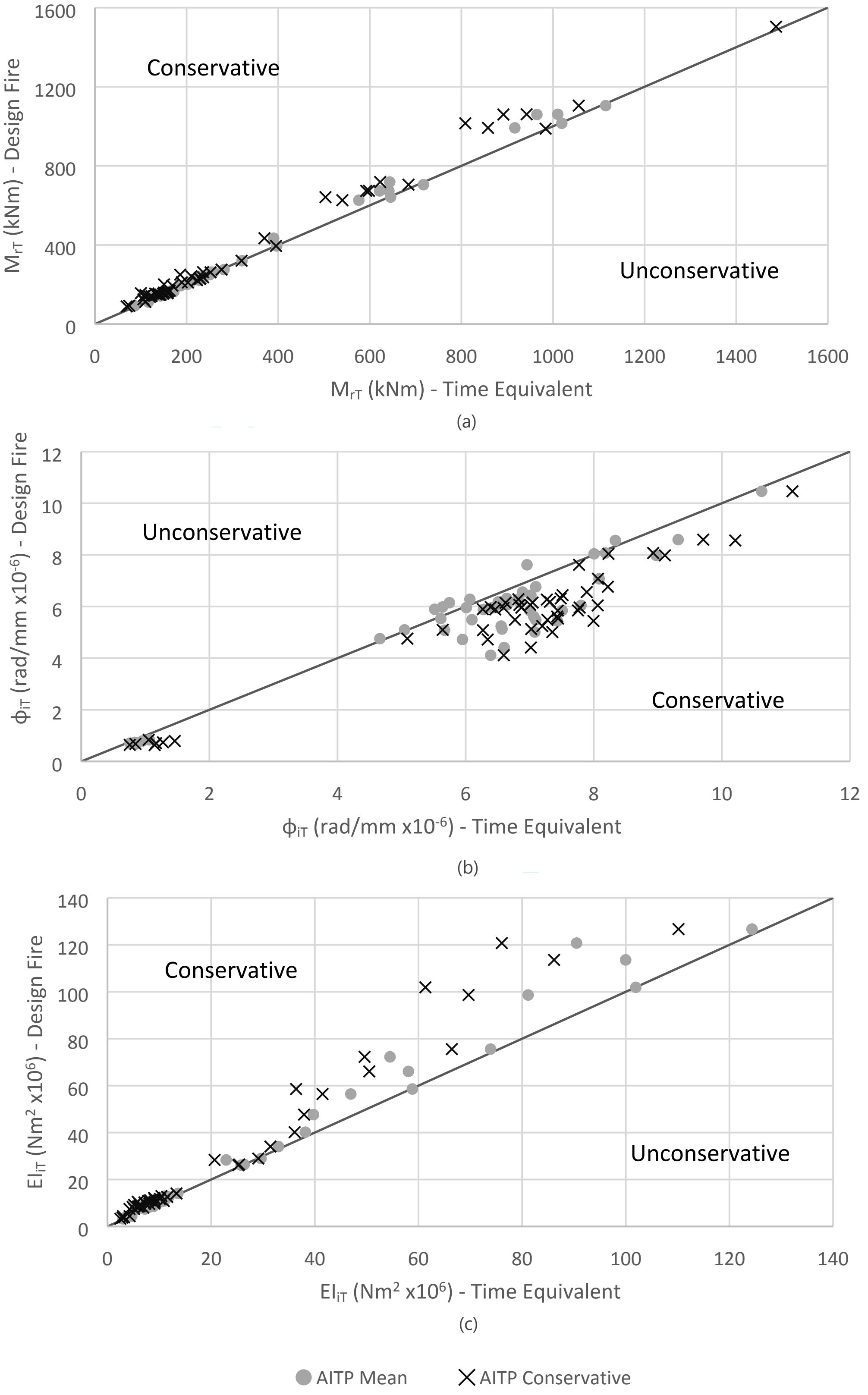
(g) FR 7 – Kirby et



(h) FR 8 – Lennon

Fig. 5: Moment-Curvature Diagrams for B1

Comparison of the remaining test cases is conducted based on the M_{rT}, φ_{iT}, and EI_{iT} (graphically depicted on Fig. 5a). Fig. 6 displays the results of the design fire predictions versus the time equivalent fire predictions. The conservative criterion achieves its intended objective, resulting in conservative approximations of lower moment capacity, larger curvature, and lower stiffness for every test case. The mean criterion presents a reasonable fit along the line of equality. The M_{rT} is captured with a high degree of accuracy by the mean t_e, with error less than 10 % for every section and design fire. The φ_{iT} and EI_{iT} generally fall within 10 % error; however, because both responses are highly sensitive to small changes in thermal strains, some outliers yield higher errors. Furthermore, in contrast with moment capacity, curvature and stiffness calculations at ambient and elevated temperatures are far more approximate (Concrete Design Handbook, 2016). Given the approximate and sensitive nature of the calculations, it is difficult for the AITP t_e to provide highly accurate predictions for φ_{iT} and EI_{iT}. It should be noted however, that the higher error predictions of φ_{iT} and EI_{iT} associated with the mean t_e are on the conservative side. The maximum error for the unconservative mean t_e predictions are always within 10 %.



(a)

(b)

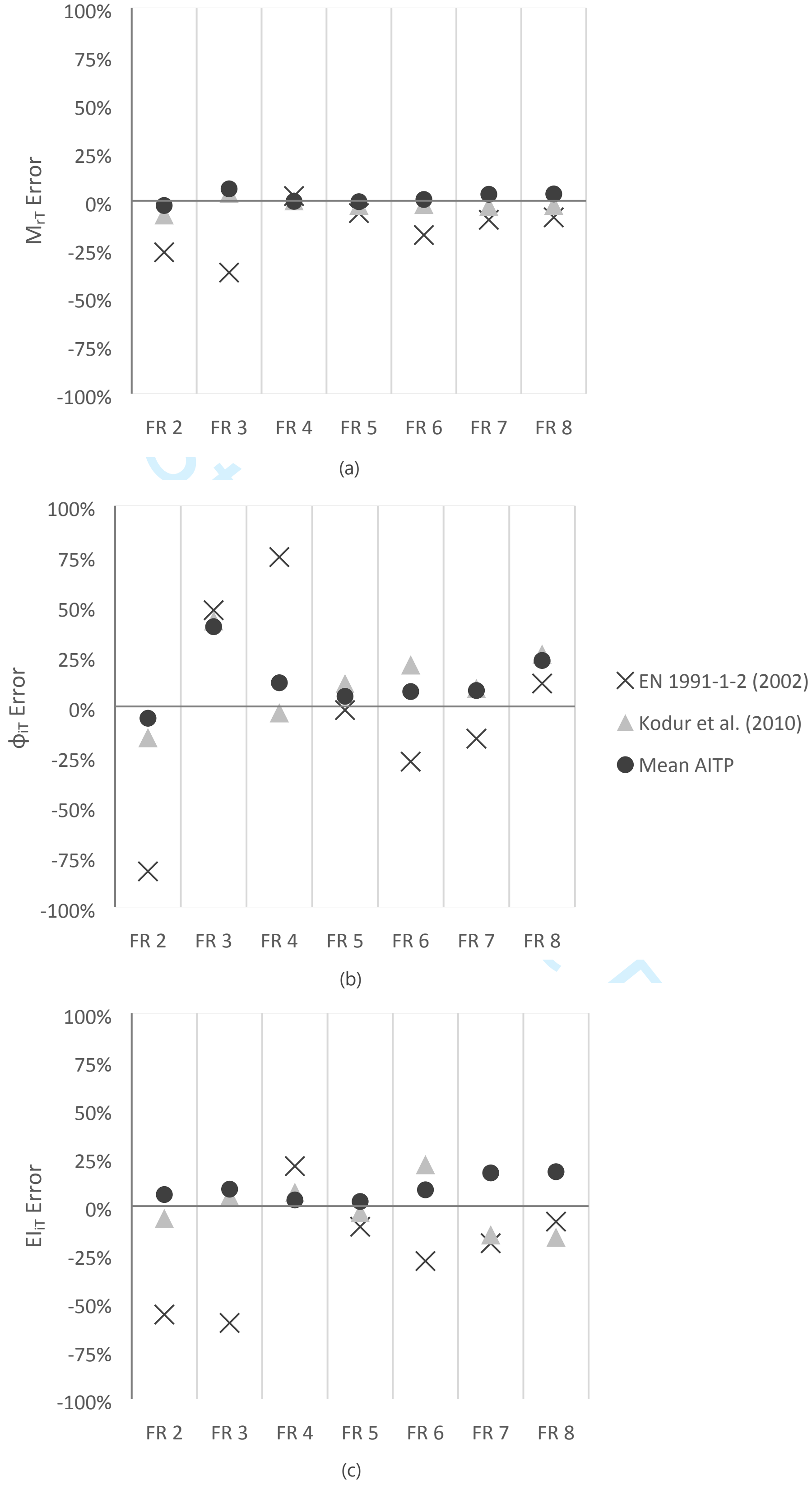
(c)

Fig. 6: Design vs. AITP t_e Response for: (a) M_{rT}, (b) ϕ_{iT}, and (c) EI_{iT}

4. Comparison with Existing Methods

There are two existing time equivalent methods that are specifically applicable for RC beams. The first is presented in the Eurocode (EN 1991-1-2, 2002) and the second by Kodur et al. (2010). The Eurocode method was derived by equating the maximum internal temperature that arises during natural and standard fire exposure. The experimental work for its derivation focused on steel sections, and as such, its applicability to evaluate the load capacity of RC elements has been disputed by Thomas et al. (1997) and Xie et al. (2017). However, given the Eurocode's clear statement of applicability for concrete elements and its prominent standing as a design standard, it serves as a solid method for comparison. Kodur et al.'s (2010) method was derived based on equating the energy transfer of a natural fire to that of a standard fire in RC beams. This method was selected for comparison as it was derived specifically for RC beams and has previously been shown to reasonably approximate internal temperatures (Kuehnen and Youssef, 2019).

Fig. 7 shows the comparison between the mean AITP t_e, the Eurocode, and Kodur et al. (2010). The comparison is made based on the moment-curvature responses of M_{rT}, φ_{iT}, and EI_{iT}. The three responses are recorded as a percentage error from the value calculated using the design fire. A positive error indicates the time equivalent results in a conservative estimate of the actual design fire response, and a negative error indicates the opposite. The evaluation was undertaken for the beam section B2. Fire exposure was applied consistent with the seven design fires in Fig. 4, allowing for assessment of the methods over a range of possible natural fire events.



(a)

(b)

(c)

Fig. 7: Flexural Response of B2 for Existing Time Equivalent Methods

From Fig. 7, the mean AITP t_e presents a high degree of accuracy in comparison with the existing methods. The Eurocode approach produces significantly deviant results across all three responses. The φ_{iT} in particular is poorly approximated by the Eurocode, with results ranging from 82 % unconservative for FR 1, to 74 % conservative for FR 4. Considering the inaccuracy of the Eurocode, it is evident that the consideration of internal concrete temperatures is critical to the determination of a t_e for RC elements.

Kodur et al.'s method presents a good level of accuracy, often producing comparable results to those developed by the AITP t_e. Although in general, the AITP t_e produces slightly more accurate results. It should also be noted that the AITP t_e is often conservative when compared to Kodur et al.'s results. This is most evident for the EI_{iT} approximation during exposure to the experimental fires of FR 7 and FR 8. In this case, both methods record errors greater than 10 %, but the predictions of the AITP t_e are conservative, while those of Kodur et al.'s method are unconservative.

The conservative AITP t_e is not displayed on the figures. However, it should be noted, that given the same testing parameters, the conservative AITP t_e is the only method that consistently recorded conservative results for all responses and fire exposures.

6. Conclusion

The AITP t_e method was assessed based on the flexural response of RC beam sections. Using a finite difference software developed by El-Fitiany and Youssef (2009), the M-φ relationship of RC beams during fire exposure was developed. A parametric study was undertaken to compare the

M-φ response of beams exposed to a range of design fires and standard fires with an AITP t_e duration. To assess the AITP t_e for a larger number of cases, three key responses from the M-φ relationship were selected for evaluation: maximum moment, initial curvature, and initial stiffness. Evaluation of the key responses displayed good correlation between the AITP mean t_e and the design fire. Additionally, the conservative time equivalent produced a M-φ profile with lesser moments and larger curvatures for every test case. Further comparison was undertaken with relation to existing time equivalent methods, demonstrating the improved accuracy of the AITP t_e in approximating the flexural response of RC beams.

Conflicts of interest

Robert Kuehnen, Maged Youssef, and Salah El-Fitiany declare that they have no conflict of interest.

Acknowledgments

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