Non-standard Large-Scale Fire Tests of Structures: A Mini Review

Ibrahim Almeshal, B. H. Abu Bakar, and Bassam A. Tayeh

Abstract Testing of large-scale structural fire has seen a resurgence in recent years, after nearly a century of using the test of standard fire resistance to understand how structural members respond to fires. The regulatory and scientific communities are grappling with a host of issues related to demonstrating adequate structural performance utilizing unrealistic temperature–time curves that are applied on isolated structural members. As a result, non-standard fire testing that is done on a large scale with real fire rather than conventional fires is gaining popularity. Several non-standard, custom-made testing facilities have recently been developed or are almost finished. Over the last three decades, non-standard fire testing has revealed substantial faults in our knowledge of real-world building performance in the face of real-world fire; in most cases, these problems would not have been discovered in tests of conventional furnaces. This study provides a brief overview of necessary non-standard structural fire engineering research conducted on a wide scale in recent decades. It highlights gaps and study requirements based on past research findings and the writers' evaluation of the information. There is also a summary of comparative research needs evaluations that have been conducted or presented in the last ten years. The overall goal is to identify knowledge gaps and guide future studies in structural fire engineering, especially large-scale experimental studies focusing on reinforced concrete structures.

Keywords Non-standard fires · Standard fire testing · Fire resistance

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1 Introduction

One of the most serious environmental risks is fire, and the safety design to mitigate this risk is an essential aspect of civil construction design [1, 2]. Natural catastrophes such as floods and earthquakes and events such as fires can cause structural damage. Every year, fire damage targets about 2.5% of all residential structures worldwide [3]. One of the most severe occurrences that have occurred in Malaysia is fire. Year after year, fires grow, notably in residential structures, with the most significant fire rate among building types [4]. Figures 1 and 2 depict the overall number of fire cases and fires in Malaysian residential structures. Between 2008 and 2018, Malaysia saw 383,621 fires, resulting in RM25 billion in damages [5]. These occurrences push an engineer to think more imaginatively and innovatively while designing a structure to prevent or postpone a fire.

It is crucial to comprehend fire behaviour and the impacts of thermal exposure on structural components in today's fast-changing built environment for the continuous supply of design strategies of fire protection [6–8]. Fire behaviour concepts generated from enclosure fire research have historically affected general structure design considerably [9, 10]. Most fire tests in recent decades have been conducted on single isolated structural elements (i.e. walls, slabs, beams and columns) that have been heated in a furnace. Such experiments do not reflect the behaviour of a whole structure in the event of a fire [11, 12]. Member interaction influences many aspects of structural behaviour. Hence, isolated element testing cannot predict or detect structural continuity. The support and loading conditions of any structural element can be altered by interactions between multiple structural parts in a whole system. This change might result in structural behaviour that is totally different from that predicted by the initial combination of loading and boundary conditions. In reality, structures

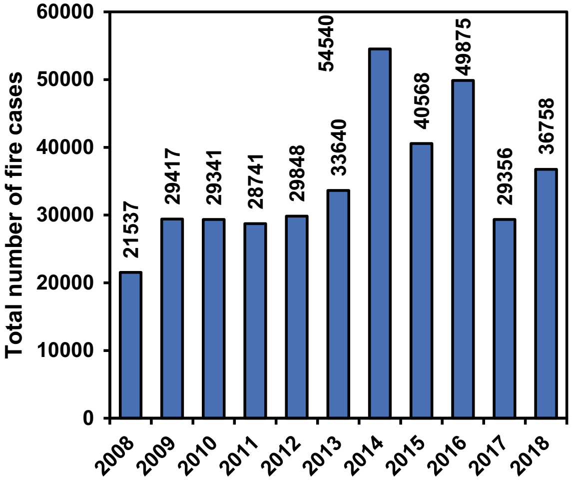
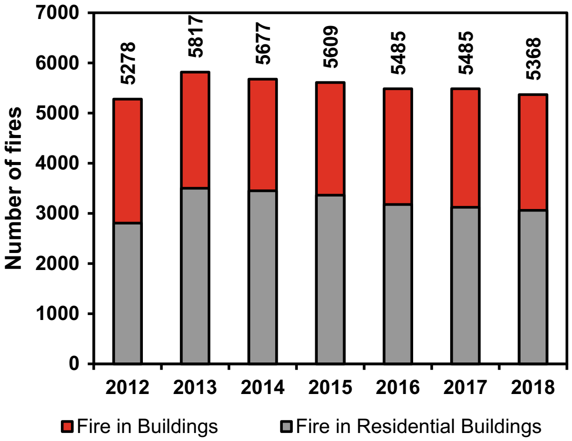


Fig. 1 Fire cases in Malaysia

Fig. 2 Fire in buildings and contents



exposed to fire hazards perform significantly better to what is anticipated in standard tests [13]. A natural fire in a fundamental structure does not follow the usual temperature–time heating curve. In fact, many significant parameters in full-scale compartments are not considered in standard fire tests such as structural continuity, boundary conditions, restraint, redistribution and membrane activities. Traditional fire tests utilizing a fire furnace for single members can only reveal local failure of specific members and cannot offer adequate information on the collapse of the entire structure. Individual member tests, as a result, provide little insight into overall building behaviour, needing full-scale fire testing to get this information [14]. After more than a century of demonstrating sufficiency using standard contrived temperature–time curves to test isolated single structural members, the time has come to move forward. Both the scientific and regulatory communities are now using the standard temperature–time curves to determine the fire resistance of single-element on isolated structural components [15]. During the preceding three decades, non-standard fire testing revealed substantial faults in our comprehension of real structural behaviour during real-world flames; in the majority of cases, these defects would not have been identified in typical furnace tests. Fire temperature distribution in big space fires differs from that in small compartment flames, according to full-scale fire studies on large space buildings [16]. Heat transmission and thermal deterioration in assemblies subjected to real flames differ from that in a homogeneous furnace exposure, according to experience [17, 18]. A full-scale experimental series is being conducted to examine and define flames in significant open-plan areas, such as those seen in modern buildings [19]. Several non-standard, custom-built testing facilities have also lately been built or are approaching completion [15].

Buildings that have collapsed due to actual flames (such as the World Trade Centre) [20] and Delft University of Technology's Faculty of Architecture Building [21] demonstrate that structural performance in actual flames is thought to be more complex than in furnace testing. A fire-protection design that is based on furnace testing may not be conservative when the influence of fire-produced temperature gradient is considerable and fire spreading occurs. As a result, testing structures in realistic flames has become a priority in the transition to fire-protection design in structural engineering, and the establishment of improved fire-testing procedures has been a major topic of research. As a result, there is still a considerable need for a better knowledge of the failure processes of structural systems in fire and the improvement of existing design techniques, both pre- and post-fire [22].

It is known that the concrete structures have a complex behaviour in fire. This mini review study aims to present a constructive criticism on the standard fire testing and to provide some of the research that used the non-standard fire furnaces on concrete structures. This paper addresses a discussion on simplified methods that have been utilized effectively for many years for designing concrete members and structures to withstand the impact of real fires.

2 Criticisms of the Standard Fire Test

There are several flaws in standardized structural fire resistance testing [23]. Before giving a review of existing material and previous research on standard large-scale fire, it is worth going over some of the previous reviews that have addressed this or comparable topics:

- Two essays regarding the history of ASTM E119 were written by [24]. The authors confirmed that the ASTM E119 standard was not based on information on building fire intensities. The fire standard was established based on a single variable that determined the intensity levels. While several countries have a viable alternative for the "standard" fire, the US testing technique has remained unchanged since 1918 [24, 25].
- After a workshop at the National Institute of Standards and Technology, Grosshandler [26, 27] gave a complete report on the topic (NIST). The study included several recommendations, including developing novel experimental methods for evaluating the mechanical and thermal characteristics of structure and insulating materials at high temperatures [26]. In a journal paper published in 2003, the same author made numerous recommendations about the standard fire test, including:
    - The current test techniques of structural fire resistance must address (1) structural element reaction up to ultimate failure, (2) statistical failure uncertainty and (3) a choice of classification or system of rating in units other than time, as well as accompanying recommendations.
    - To enable the transition to fire resistance design of performance-based structural, a persistent, multi-national research effort is required [27].
- In 2004, NIST also released a report by Almand et al., which included several recommendations, the most important of which are: (1) standard fire tests do not give information on a component's actual performance in a real fire; (2) no analytical or practical tools are adequate to assess the effect of alternative design

and strategies of fire protection to enlist the help of firefighters; and (3) there are no analytical or practical techniques that are sufficient to assess the efficiency of various design and fire safety measures [28].

- In discussion papers concerning the fire resistance of structures, Kodur et al. said that present structural fire safety measures have major limitations and serious knowledge gaps in the literature. The absence of substantial research efforts in this sector and the dearth of teaching and training programmes at universities are two significant causes for these restrictions [29, 30].
- Beitel and Iwankiw, commissioned by NIST, released a study after investigating 22 multi-storey fires between 1970 and 2002. According to the authors, catastrophic failure modes found in actual structures could not have been predicted using average fire resistance (furnace) testing in most situations. In all situations, structural interactions and connection response were also essential [31].
- A recent study conducted by [15] evaluated structural fire testing on non-standard large-scale compartments and agreed with [32], who indicated that standard fire test is not an accurate tool for making comparison between structures' behaviour and should not be even used to measure the performance of a single member in a real fire [32]. Despite that, the authors agreed with the fire testing industry that standard furnace testing offers benefits such as repeatability and control and is thus helpful for benchmarking and comparison testing [15].
- Gales et al. produced a book on the performance of post-tensioned concrete that was subjected to standard fire test (2015). According to the authors, standard fire testing is unable to recreate a wide range of critical behaviours that may be anticipated and have been observed in genuine unbonded post-tensioned buildings during natural flames [33]
- The standard temperature–time curve for buildings was developed by Gales et al. [34]. According to the author, the standard temperature–time curve (ASTM E119) has not changed appreciably since 1916. Worse, science does not support the heating curve's portrayal of an actual fire [34].

3 What is the Solution to Predict the Fire Resistance of Concrete Structures?

Both actual fire and fundamental structure should be applied through an experimental or numerical model to comprehend a structure's fire resistance fully. That simulation has two parameters: the structure, which is challenging to build due to the high expenses. The majority of prior research on concrete fire behaviour focused on: (1) materials and partial members; (2) reinforced concrete (RC) member/single element; (3) sub-frame assemblies; (4) transiently simulated restrained assemblies; and (5) actual buildings. The second is the sort of fire, which is categorized as follows:

(i) Elevated temperature exposures (transient or steady state): increasing the temperature in linear association and above 100 °C, when hydrothermal reaction starts [35]. This type of fire tests is often used to determine the fire resistance of building materials.
(ii) Standard fires: are time–temperature curves provided by international institutes such as ISO 834, BS 476 and ASTM E119. The test involves exposing a test specimen to a standard fire that is controlled to maintain specific temperatures for a set amount of time [36].
(iii) Equivalent fire severity to a standard fire: is beneficial where standard fire resistance test results are available; however, time equivalent formula may not be accurate beyond the data range for which they were calibrated. It is far more precise to calculate structural fire resistance by using the first principles [37].
(iv) Parametrically fires: the parametric fire model presented in Annex A of Eurocode 1 [38].
(v) Localized fires: Unless there are highly unusual circumstances, every fire in a building begins as a tiny, localized fire. When a fire flashes over, it loses its localized nature. Even a localized fire may have a large influence on a structure. This depends on the relative location of the fire with respect to the structural components and on the type of the structure in general [39].
(vi) Zone model: separating the fire into few numbers of major zones such as the hot smoky gas layer and the plume under the roof. This method is considered simpler compared to the field model. It works to rely on empirical and well-established correlations and equations for smoke and heat transfer between these zones [40].
(vii) Field model fire: is a field of applied mathematical modelling that deals with fire dynamics. To analyse the behaviour of fire, the fundamental laws of fluid mechanics and heat transfer are considered as represented in the laws of conservation mass, momentum and energy. Along with other concepts and equations that support the field modelling method, there is the fundamental basis of the fire field modelling [41].
(viii) Real fire/Non-standard fire: The term “real fire” is often used to describe fires that start within structures, either inadvertently or intentionally [42].

There are two difficulties with concrete in a fire: mechanical property degradation as temperature increases, induced by physicochemical variations in the material during the heating process; and explosive spalling, which leads to material loss, section size reduction and reinforcing steel exposure to high temperatures [35]. In the case of concrete structures, there are three types of failure criteria: (1) structural adequacy (load-bearing capability), (2) structural integrity (flame resistance) and (3) structural insulation (the capability to stop fire from spreading due to an extreme elevation in the temperature of a non-heated face).

The reader can see from the preceding section’s analysis of building kinds, fire types and failure criteria that there are numerous possibilities for selecting the sort of fire that can be executed on a complete compartment. The standard fire is an essential time–temperature relationship that academics use for comparison rather than to assess a building's actual performance in a fire. A genuine fire (non-standard) should be carried out on an actual structure (large scale) to fully understand the performance of a fireproof building, which will be described in the next section.

4 Non-standard Large-Scale Fire Test of Reinforced Concrete

Even while key structural parts work well when isolated during normal furnace testing, it is worth mentioning that the concrete buildings, rather than focusing on standardized tests, pioneered what is now known as unique non-standard fire tests on structural "assemblies" of concrete. In the 1950s, for example, early research on beam-slab assemblies and two-way post-tensioned concrete slabs in the USA used a combination of slabs and beams to investigate the two-dimensional response of these assemblies (Troxell 1959). Despite the fact that this early research produced a lot of furnace test data, the current study focuses on more recent endeavours. As a result, these "historical" tests are no longer valid.

Several academics have proposed a large-scale non-standard fire test to address all of the above-mentioned problems, including [15]. However, few non-standard structural large-scale fire tests on RC structures have been conducted owing to the common perception that, cover spalling in the absence of explosive cover, concrete structural components outperform exposed steel parts in conventional furnace testing. As a result, the concrete industry appears to see little value in utilizing time-consuming and expensive testing programmes to examine and demonstrate the potential advantages of considering the overall structure interactions and ability of structure members to carry the design load such as membrane action and load-carrying mechanisms in RC structures during a fire hazard. Because of the evident economic benefits and competitive advantages of non-standard large-scale structural fire testing, the steel construction industry has actively promoted this testing methodology. Despite this, there is a tiny amount of concrete structuration that is significant. Building behaviour in fire is more complex than what present prescriptive standards would indicate, according to available concrete testing. This might have both positive and negative implications for concrete structures in the event of a fire [15].

Concrete constructions offer both potential benefits and hazards in a fire [15]. Many researchers have identified the use of custom-built or modified conventional furnaces to examine unique structural member performance concerns or certain sorts of concrete structures that are difficult to investigate using a normal "component" method. A few notable cases are summarized in Table 1.

Table 1 Non-standard large-scale RC fire tests

Researcher	Material type	Structure/element type	Significant outcome
Van Herberghen [43]	Unbonded post-tensioned RC	Flat floor slabs	• The authors used amended standard furnace for studying the performance of the floor under fire • To ensure a better understanding of post-tensioned RC slabs resistance in fire, numerical models could be used after careful validations
Baily [44]	Cast-in-place RC	Seven storey building 3 × 4 bays and 22.5 m × 30 m in plan	• After 25 min, a maximum temperature of 950 °C in the gas phase was measured before the equipment was turned off (the temperature was assumed to have kept increasing) • Vertical displacements at the building's perimeter were more significant than those near the centre, and there was no trace of a stabilizing plateau • Designers should also consider concrete spalling when selecting fasteners between compartment walls and the soffit of concrete slabs
Kelly and Purkiss [45]	Unbonded post-tensioned RC	Three-span continuous slab strips	• The authors used amended standard furnace for studying the performance of the slab under fire
Bailey and Lennon [46]	Precast RC	Slabs on steel beam flooring systems	• The optimal average temperature in the gas phase was above 1000 °C; during the cooling phase of the fire, the edge units cracked locally; however, this did not result in a loss of overall load-bearing capability • Due to thermal expansion limitations, there was evidence of a lateral compressive strip forming at the ends of the units, which would have increased the units' flexural and perhaps shear capacity

(continued)

Table 1 (continued)

Researcher	Material type	Structure/element type	Significant outcome
[42]	Post-tensioned RC	High-strength columns and slabs	• Adding fibres to a high-strength mix reduces spalling significantly • Spacing the column ties closer together has no effect on how much spalling occurs • Polypropylene fibres should be considered for this sort of construction since a post-tensioned slab containing a single aggregate type spalled poorly • One of the post-tensioned slabs showed no signs of spalling, whereas another spalled on both ends for no apparent reason
Wong and Ng [47]	RC	40 unloaded columns, in an actual building	• Insulation, fire-resistant coating materials, polypropylene fibres, or wire mesh should be used in high-strength column members to prevent spalling. These tests are not applicable to real-world fires in structures. The testing techniques utilized in this study were unusual, even for non-standard structural fire testing
Ring et al. [48]	RC	Four large-scale non-standard fire tests on "frame-like" structures	• There are several advantages of using polypropylene fibres to prevent explosive spalling in a fire

5 ACI 216 and IBC 2021 Methods

The technique utilized by the American Concrete Institute (ACI 216) committee and the Masonry Society (TMS) to find out how fire-resistant concrete members (ACI/TMS 216.1-14(19)) will be presented in this part. Although ASTM E 119 testing is arguably the most dependable method, due to the cost, effort and time required to create and test the assemblies on large scale, this method is impractical and, in many cases, led to unreal results. The methodologies and specifications used in ACI 216.1 were developed based on several previous fire studies that were done between 1958 and 2005, and they are still the most widely used in everyday assessment and design practices. Based on the heat transfer endpoint, the fire resistance of a specific concrete member or full assembly is calculated by determining its equivalent thickness (only the concrete core) and then relating it to the corresponding fire resistance duration in the tables and charts. The correct thickness of slabs and solid walls that have level surfaces is the same as solid wall thickness. ACI 216.1 formulae must be used to estimate the equivalent thickness of walls and slabs with gaps, undulations, ribs, or several layers of different materials (e.g. a sandwich of concrete, insulation and concrete) [49].

ACI 216.1 specifies an analytical method for assessing flexural members' fire resistance. This approach entails calculating the true temperatures of the concrete and the steel reinforcement and then assessing the materials' characteristics at those temperatures. The bottom joyful moment steel, according to the method, will be exposed to high temperatures and start to decay before the top concrete and reinforcement. It enables the member's moment to shift from a weaker, positive zone to a more significant, negative zone. Once the part or assembly has been determined to have sufficient comparable thickness and once the member or assembly has been determined to have sufficient equivalent thickness to satisfy the heat transmission endpoint, it must be determined whether the reinforcing steel has sufficient cover to prevent excessive heat from reducing the yield strength to the point where it can no longer carry the load. The necessary fire rating, aggregate type, restrained or uncontrolled construction and prestressed or unstressed reinforcement all had an impact on the slab cover requirements [50].

All around the world, national building regulations control the fire resistance of different parts and assemblies that form a building structure. Structural frames (consisting of columns and beams), load-bearing walls and floor systems must be able to endure the stresses and strains imposed by fully developed fires while also carrying their dead and superimposed loads for the needed duration. Prescriptive rules for building components are presented in Chap. 7 of the 2021 International Building Code (IBC). This chapter's tables explain various combinations of materials and finishes that fulfil certain fire resistance ratings for a building. The techniques or approaches listed below were specified:

(i) Prescriptive fire resistance: in this method, tables are used to describe fire resistance ratings for using insulating materials such as plaster and unit masonry. The table provides fire resistance periods of these insulating material based on the thickness.
(ii) Calculated fire resistance: in this method, the fire resistance can be calculated through tables and figures which are in compliance with the tables found in ACI 216.1, with the exception of the provisions for the use of high-strength concrete columns found in ACI 216.1.
(iii) Engineering evaluation based on a comparative analysis of the designs of building elements, components or assemblies with fire resistance ratings as indicated by ASTM E119 or UL 263 test procedures.
(iv) Fire resistance designs are documented in approved agency by IBC or approved sources.

6 Conclusion and Research Needs in Structural Fire

- Fundamental techniques for defining fire settings have been utilized in the past, such as assuming homogenous temperatures or using basic temperature–time curves, both of which are inaccurate depictions of a real fire. There is now a need for more thorough research on variations in concrete mixtures, including temporal as well as spatial differences in heating. To understand the holistic behaviour of concrete buildings, additional testing of whole concrete structures in real fire is required, including interconnections between different structural components, and to assist in the validation of sophisticated computer models. Detailed research of concrete building performance in real-world fires can also aid our knowledge of real-world behaviour.
- The behaviour of concrete in fire is currently unknown, and other studies are needed in most themes. The physical performance of concrete degrades in diverse ways based on the concrete mix's details, notably the moisture content and critical climatic variables like maximum fire temperature and duration. It is vital to do a systematic study on the impacts of various heating settings on concrete.
- Linking these finely detailed small-scale behaviours to the performance of whole structures in realistic fires is more difficult. Using exact models to anticipate spalling behaviour remains a severe challenge, despite substantial advances in modelling the mechanical of concrete structures, especially when the basic function of LITS is fully accounted for. Moreover, the capacity to forecast structural interactions that may contribute to failures is lacking.

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