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Structural fire resistance: Rating system manifests crude, inconsistent design

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ABSTRACT

This paper highlights a shortcoming in the current system of structural fire resistance design, proposes how it can be addressed and shows how the perceived barriers to change can be overcome. It is an opinion piece intended to stimulate discussion.

Whilst structural fire engineering knowledge may be relatively underdeveloped compared to other engineering disciplines, the industry has made great progress in recent decades in understanding and analysing fire behaviour and the response of structures, as well as developing fire protection products that can be accurately specified to meet performance criteria. In addition, through modern fire and risk engineering there are also methods to establish the appropriate fire resistance rating for a building (or element) based on risk profile, fire loading, building fabric and potential ventilation amongst other things. It is the objective of many within the industry for structural fire engineering to become an integrated part of the design process, ultimately leading to safer and more efficient structures. However, this paper questions whether current structural fire resistance design methods achieve the consistent level of crudeness required for this, or whether the means by which structural performance in fire is quantified, standard fire resistance, represents a weak link that undermines the entire process.Although the concept of standard fire resistance, benchmarked against performance under normalised furnace test heating regimes, is useful in that it allows for the comparison necessary to safeguard consistency across products, design methods and geographies, the historic 15-min fire resistance increments (for example 60, 75, 90 min) result in inconsistent levels of safety. Refined grades, as in fact already allowed under fire resistance testing standards, would yield significant benefits for reliability and design efficiency. The paper uses hypothetical case studies to exhibit the merits of refined fire resistance grades and explains how implementing the enhanced classification system may be readily achievable.

Introduction

In general, since the turn of the 19th century there has been steady improvement in the means by which adequately safe structural response in fire is designed for and implemented. The aspirations for acceptable building performance have become better defined and documented in regulatory literature and design codes. Understanding of fire dynamics and the

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thermo-mechanical behaviour of construction elements and buildings as a whole has advanced greatly. Fire protection products (intumescent paint to steel for example) have evolved to be highly effective systems for which thickness can be specified to the micron to meet given performance criteria. However, the fire resistance ratings against which satisfactory behaviour of structural elements is benchmarked (determined by the duration of standardised furnace-test heating regimes experienced by an element before defined performance criteria are breached) are specified in 15-min intervals (for example 60, 75, 90 min) that relate to figures in prescriptive guidance which have remained largely unchanged since the post-war era [1]. This despite the fact that fire resistance test standards [2] state that any furnace test duration may be applied. Does the 15-min grading system therefore represent a crudeness that limits the reliability and consistency of the overall design process? This paper presents the authors' views on this issue, and is posed as an opinion piece intending to stimulate discussion amongst the fire safety community.

Structural fire engineering: innovative design, arbitrary solutions

The aspirations of architecture and structural design are advancing ever further and the limits of the industry's understanding of material and structural response in fire are being stretched. Innovative structural systems are being employed, traditional materials are being used in novel ways and built spaces are being created in shapes and sizes previously not envisaged. As such, the applicability of prescriptive codes in fire resistance design is rightly coming under increasing scrutiny and performance-based fire resistance design, broadly referred to as structural fire engineering, is becoming increasingly important in delivering structures that meet life safety and property protection objectives. Ensuring considered application of engineering methods and avoiding blind application of prescriptive codes will be crucial to delivering safety in the next generation of buildings, particularly in the developing world where international best practice is often seen as a panacea for all buildings. When structural fire engineering is integrated and considered as part of a holistic fire resistance design approach, considering all project goals and the full life cycle of an asset, it can also help meet the growing expectations of investors and society generally for sustainable, robust, cost-effective buildings [3].

In an effort to maintain pace with evolving goals and design challenges, recent decades have seen increased sophistication in the input parameters and analysis methods used in structural fire engineering. In her provocative 1995 paper "Magic Numbers and Golden Rules" [4], Margaret Law challenged the fire safety community, particularly those involved in regulation, to allow designers to implement judgement and engineering-based rules in the development of fire safety solutions, as opposed to the unthinking application of prescriptive rules for which the underpinning assumptions and limitations may no longer be relevant. Only through a holistic approach, incorporating performance-based methods as appropriate, can fire engineers deliver consistent, acceptable levels of safety in buildings that are also fit for purpose, meet client aspirations and are delivered within the often competing constraints. The industry has made progress on this front but, as fire engineers around the world including the authors will attest to [5], code-based design (for example, in accordance with BS 9999 [6] or Approved Document B [7] in the UK) is still typically viewed as the "target" for safety, and there is a long way to go before prescriptive "golden rules" and performance-based engineering are given the respective appropriate consideration they warrant.

The engineering analysis that supports performance-led design must be founded on sound principles, and applied with a rigour and accuracy appropriate to the particular technical challenges presented and solutions proposed. As Elms professed on engineering generally in 1985 [10], the design process is only as strong as its weakest link and "the choice of level of detail in any part of an engineering procedure must to some extent be governed by the crudest part of that procedure". In short, if one part of an answer is overly crude, it will render the refinement and complexity of any other methods largely irrelevant. As design methods, codes and understanding evolve, certain areas evolve at faster rates than others and, as such, inconsistent levels of crudeness or accuracy are almost unavoidable. Good engineering should recognise the crudest inputs or procedures in a process, and seek to reduce their uncertainty or the impact that their uncertainty will have on the validity of the process.

This principle of achieving a "consistent level of crudeness" has since been applied to the specific field of structural fire engineering by Buchanan in 2009 [11] as part of his challenge to structural engineers and fire engineers to talk to one another, and again by Angus Law in 2014 [9] in highlighting the challenges of delivering designs that balance the goals, constraints and products required on a particular project. The latter paper highlights that not only are the fields of fire engineering and structural fire engineering evolving disciplines that are still research-led in many facets and therefore far from exact, there are also numerous other factors which can affect the crudeness of structural fire resistance design. These include defining the fire safety goals and consequently the performance acceptability criteria, regulatory / legislative restrictions, limitation imposed by coordination with other elements of the design and construction, and the available and viable fire protection methods.

Designers must interrogate their design methods to establish whether certain aspects are compromising the remainder of the process. There are well-documented limitations associated with structural fire engineering [9], but it is the authors' opinion that the outputs for specification of fire protection solutions (i.e. fire resistance ratings) remaining benchmarked in 15-min increments is the crudest part of the fire resistance design process and it should be refined.

Without a refined rating system, progress in the field of structural design for fire safety will continue to be constrained by the crude means in which fire protection solutions are categorised. This paper explains the numerous negative implications arising from this, primary amongst them being the delivery of inconsistent and unreliable levels of safety. Firstly however, in order to discuss the consequences of the crude rating system, the context of the fire resistance ratings themselves must be clarified.

Fire resistance is a risk-based, comparative metric – why the need for grades at all?

In the context of structures, fire resistance conventionally refers to time under defined furnace test heating (for example BS 476 [2], ISO 834 [12], ASTM E119 [13]) for which an isolated member can maintain its load-bearing capacity in fire. The standardised heating and restraint conditions in the test mean that it may have little correlation with the behaviour of an element in any particular real fire. Fire resistance is therefore intended to be a metric upon which performance of different elements and assemblies can be compared, not a measure of expected damage to, or survivability of, a structure in a real fire. Background on fire resistance testing generally can be found in the literature, e.g. [14].

The relationship between an element's response in a fire resistance test and that which may be expected as part of a wider structural frame in a real fire has become less meaningful in recent times due to advances in structural design. With the development of sophisticated analysis tools and the movement away from a reliance on standard sections sizes, structural grids, non-composite design, etc. the use of an elemental load-bearing capacity as the universal performance criteria has declined in relevance.

Notwithstanding the above, standardised fire resistance ratings are useful in that they allow for comparative benchmarking of performance expectations of one building relative to another based on the risk profile associated with the building. The fire resistance ratings quoted in prescriptive fire safety guidance and regulations around the world are typically specified on this basis, generally taking into account high-level factors such as building height, occupancy type and whether active fire suppression is in place.

The grading structure itself largely grew from and was defined by the fire protection industry and the establishment of test houses to service that industry. Taking into account the understanding of fire and structural / material behaviour in fire at the time of this evolution, as well as the costs associated with testing, it is understandable that certification of fire protection products was carried out in bands. However, the combination of ratings referenced in prescriptive guidance filtering through to the wider construction industry as perceived safety targets and standardised industry-wide product testing, has meant that the 15-min grade structure has become deeply rooted in design. In fact, more commonly, 30-min grades have emerged as the norm and above 120 min fire resistance, the system typically goes to 60-min steps.

Given that the prescriptive "magic numbers" for fire resistance were only intended to apply to "common" buildings, the challenge as laid down by Margaret Law [4] is for the industry to move away from viewing them as a panacea for safe structural fire design, and to assess performance-based alternatives on their merits at a scientific, first-principles level without prejudice on account of their departure from code guidance. To interrogate risk-based and performance-based designs analytically, it is the analysis methods, input parameters, assumptions and acceptability criteria that must be scrutinised, not the final outputs. This is true of design processes generally, not just structural fire resistance.

If designers, approvers and stakeholders have confidence in and are agreed upon the theory and figures applied in a calculation, including soft factors such as contingencies, then provided a consistent level of crudeness is achieved throughout the process, then reliable, efficient results should be achieved. The structural fire resistance design process does not achieve this consistency however and it is therefore not conducive to the application of holistic fire resistance design incorporating performance-based engineering. Although for many standard applications and buildings, "off the shelf" products and designs utilising the current fire resistance grade structure will provide satisfactory outcomes for all parties, having a system that inhibits the level of design required in less "common" structures represents a significant restraint.

As noted at the outset of this paper, significant advances have been made in recent decades in how building structures are designed for fire safety and they can be summarised as follows:

– Fire resistance design is increasingly being thought of holistically as part of the design process and a greater appreciation is being given to the objectives of stakeholders for building response in fire, and what performance can and should be expected.
– The means by which these aspirations are considered, alongside appraising the fire risks, consequences and structural reliability associated with a particular element or building, have also evolved such that the appropriate fire resistance can be specified to the minute [8,9,15].
– Great advances have been made in understanding and modelling the behaviour of fire and the response of full building structures in real fire scenarios, leading to the development of design standards (such as the Part 1–2 sections of the Eurocodes) and several other industry-accepted methods of quantifying structural performance in fire, for example [16,17].
– The design and specification of fire protection products has advanced immeasurably from the post-war era, particularly in the steel industry where fire protection systems can now be specified to the micron to meet given performance criteria.

Fig. 1 presents an indicative timeline charting the relative progress in sophistication of the various aspects of structural fire resistance design described above. Note that this graph is intended for qualitative comparative purposes only, with a view to demonstrating the evolving inconsistencies in the crudeness of fire resistance design.

Given the above, the industry should in theory be capable of achieving optimised fire protection solutions that satisfy with an acceptable degree of confidence, all project goals for life safety and asset protection, including stakeholder aspirations for additional safety or contingency to allow for future flexibility in the building. However, the outputs of such a considered and performance-led design approach must ultimately be rounded-up to the nearest 15-min grade (or as previously referenced, more often 30-min or 60-min grades) and the consequences of this crude overlay can be profound.

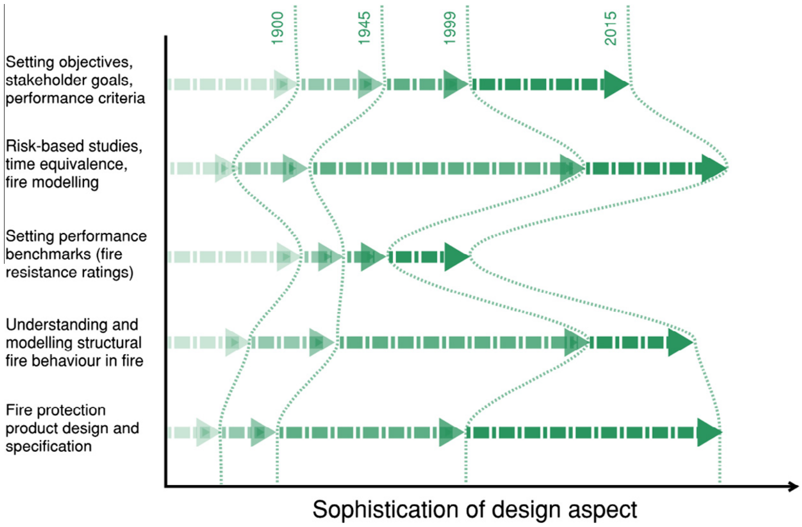

Figure 1. Indicative plot showing the relative progression in sophistication of the various facets of structural fire resistance design.

What is the problem with the current fire resistance rating system?

Three fundamental problems arise from the current system of 15-min increments:

- Inconsistent, ill-defined levels of safety are delivered. Such crude increments between fire resistance classes often require significant rounding-up of engineering output to the next grade, which many in the industry misinterpret as a comforting degree of contingency or safety factor. However, the variations in rounding-up (from 1 min to 14 min in theory) yields highly inconsistent levels of contingency, meaning that future changes in building fabric or use, or in the event that a design assumption transpires to be unconservative or a more severe fire scenario than that considered takes place, can result in an unconservative fire resistance design.
- Discussions with design teams, approvers and stakeholders tend to focus on the outcomes of any performance-based study and what it means for project costs and the perceived standards of safety, as opposed to the particular design and analysis in question. Margaret Law highlighted this problem 20 years ago [4] and her views remain just as relevant today: departures from prescriptive recommendations attract undue scrutiny, to levels which would never be applied to solutions that comply with the "magic numbers", at the expense of rational, risk-based and engineering-based review. The implications of a 15-min or 30-min change in fire resistance are often viewed as too much reduction in safety for an approver to accept (or indeed an unnecessary increase in the eyes of a client or project team if, in the unlikely event that, a fire engineer was to suggest a fire resistance higher than the prescriptive guideline was appropriate) or too risky for a project team to pursue without confirmation of approval, regardless of what an engineering assessment demonstrates.
- The efficiency of the final solution is compromised, sophistication in the design methodology is negated and benefits of an all-inclusive, integrated design approach are limited if not wasted. If structural fire engineering is to be incorporated as a core design discipline to the overall advantage of the design, it needs to be quantifiable in a manner that allows accurate engineering-based assessment, metrics for incorporating various stakeholder aspirations (for example the differences between designing for a structural reliability purely intended to prevent disproportionate collapse and one intended to meet higher standard, life safety-based requirements) and is less dependent on subjective regulatory approvals, as per the previous point above. "Rounding-up" factors, owing to the 15-min increments, which can differ by an order of magnitude do not lend themselves to accuracy. The consistency of crudeness sought after in any engineering process is therefore not attained.

Given the authors' first-hand experience of the above issues resulting from the current fire resistance rating system, this paper proposes refined fire resistance grades.

How would refined fire resistance ratings address these problems?

Moving from a fire resistance rating system that is governed by arbitrary, historic lines in the sand to one that is independent of prescriptive magic numbers and instead capable of accommodating any output from engineering analysis, would address the key concerns discussed in the previous section. More consistent and definable levels of safety could be delivered, the focus of performance-based solutions could focus less on the output and more on the engineering involved, and more efficient solutions that take greater advantage of the growing understanding of structural fire behaviour could be achieved.

As noted in the introduction, fire test standards [2], do not restrict fire resistance ratings to specified bands. The ratings are benchmarked against standardised, continuous temperature–time regimes and as such, all points on the temperature–time curve are valid. Therefore, fire resistance as a metric can be specified at any point without compromising the intent of the rating: to comparatively quantify structural performance in fire based on risk. The current testing system therefore already has capacity to accommodate refined methods of assessing risk and / or fire severity. By opening up the entire fire resistance curve for specification of fire protection solutions, the full benefit of these and other engineering methods could be realised and the advantages of this for design could be considerable. In addition to the above-mentioned benefits, by specifying fire protection solutions more closely based on fire engineering assessment and thereby more efficient, there may be greater potential to preserve heritage buildings, achieve sustainability aspirations and facilitate innovative architectural aspirations that may otherwise be curtailed by an overly crude fire resistance design.

Hypothetical study demonstrating the shortcomings of the 15-min fire resistance increments

Two hypothetical cases have been assessed in order to explore the differences between the current 15-min interval system for fire resistance ratings and a system with ratings refined to 1-min grades.

For the thought experiment, two 28 m tall, unsprinklered office buildings in the UK have been chosen. As such, from a prescriptive perspective (for example, in accordance with AD B or BS 9999), both are identical and should have a fire resistance of 90 min. However, the buildings differ in their form of construction, amounts of potential ventilation openings (windows) on their façades and their compartments sizes, as summarised in Table 1. As such, when risk-based and / or performance-based fire engineering methods are applied to establish the appropriate fire resistance for each building, two very different answers are obtained: 74 min is determined for Building A and 61 min is determined for Building B.

In practice currently, when specifying the fire resistance for these two buildings, the fire engineer would need to round up both of these figures to the nearest commercially useable fire resistance rating, namely 75 min for both.

For Building A, this equates to rounding-up by 23% but for Building B the figure is only rounded-up by 1.4%. This demonstrates a considerable inconsistency in the level of conservatism applied to the analysis outputs. The "rounding-up" is often seen as a contingency factor or additional level of comfort by approvers, but these figures show that the contingency can range from negligible to potentially over-conservative. Such an approach does not lead to safe, reliable design. Furthermore, unless the basis of the fire engineering analysis is retained for the lifetime of the building and taken into account as part of any future refurbishments, the problem could be exacerbated as it is quite possible that changes to the building layout or use could lead to a performance-based fire resistance that exceeds that originally designed for and implemented.

One way to overcome this risk would be to introduce pre-defined and agreed contingency factors, if required to facilitate future flexibility or provide comfort to approving authorities over the methods used to define the fire resistance for the building. However, given the crude 15-min rating increments, applying a contingency of say 5% to the fire resistance of Building B would move it into the 90 min fire resistance bracket, which could be considered overly conservative.

It is clear that the 15-min bands in which the outputs are specified have a significant bearing on both the consistency and efficiency of the design, and appear to be the crudest part of the design process by a distance. The alternative case considered in this study demonstrates how refined fire resistance ratings can avoid the implications of crossing rating bands, and thereby more readily facilitate the inclusion of consistent contingency factors. Applying a notional 5% contingency to both buildings, Building A would have 64 min fire resistance and Building B 78 min.

Table 1
Summary of the characteristics of the example buildings assessed.

	Building A		Building B	
Occupancy	Office		Office	
Height	28 m		28 m	
Sprinklers	No		No	
Prescriptive fire resistance	90 min		90 min	
Construction	Steel frame, concrete floors / core		CLT construction throughout	
Glazing	Fully glazed façade		Limited glazing	
Compartmentation layout	Open-plan floor-plates		Separate offices / compartments	
Performance-based fire resistance	61 min		74 min	
	Fire resistance increments		Fire resistance increments	
	15-min	1-min	15-min	1-min
Design fire resistance	75 min	64 min	75 min	78 min
Pre-defined contingency factor (%)	–	5	–	5
Rounding-up to next increment (%)	23	–	1.4	–
Total contingency in design (%)	23	5	1.4	5

As a result of this alternate approach and the inclusion of a pre-defined contingency factor, both buildings' fire resistance more accurately reflects the objective of the risk-based and performance-based methods, as demonstrated in Fig. 2. As such, a better balance has been found between reliable levels of safety and optimising the design.

The 5% pre-defined contingency factor has been chosen arbitrarily for demonstrative purposes. The value could be selected to suit the particular constraints and objectives of a particular project, including the views of the end user, their insurers, authorities having jurisdiction and other relevant stakeholders regarding future changes in the building or other uncertainties. Depending on the levels of sophistication and conservatism within the methods used to calculate a building's fire resistance, amongst other things, contingency factors may not be need to be applied to the design fire resistance.

Why are 15-min intervals being used then?

The arguments and example study presented in this paper outline the benefits of refining fire resistance ratings and at the outset it was stated that test standards for fire resistance in fact currently allow for an element to be assessed and certified to any fire resistance rating. What reasons could there be then for retaining the current system?

- Firstly, the fire safety industry is a stubborn one that has traditionally not been quick to embrace change. This is largely because history indicates that the simple rules, when applied to straightforward buildings, result in a level of life safety generally considered to be acceptable by society. The entrenched perceived conservatism and the "if it ain't broke don't fix it" attitude is typically only challenged and scrutinised in the aftermath of disastrous fires, at which point it is often concluded that the simple, prescriptive rules must be changed or the applicability restricted. Instead of this reactive, piecemeal approach, it is the authors' view that a proactive change in the grading of fire resistance is achievable and warrants consideration by the fire safety community.
- A reason likely to be put forward is that the current 15-min grade system is so embedded within the industry that to change would be more trouble than it is worth. It is true that everything from prescriptive guidance to insurance documentation to specification for partition wall assemblies to fire doors are benchmarked in at least 15-min (often 30-min) grades. Fundamentally however, such items may not need changing, as the proposed refinements in ratings apply specifically to fire resistance of elements of structure and only where performance-based methods have been applied. Technically, there is no reason why a building that has been determined by fire engineering to warrant a 52 min fire resistance, could not include 60-min fire-resisting partitions for compartment walls, FD60 fire doors, 60-min fire-rated firestopping, etc. (as corresponding 52-min rated products do not exist) but have elements of structure designed and protected to achieve 52 min fire resistance.
- The certification process for fire protection products, such as intumescent paint for steel, may need to be adapted. Like many forms of product regulation, it may be possible to certify the overall process along with select data points (i.e. fire resistance ratings), as opposed to every data point, with further data for individual fire resistance ratings to be provided upon request. Intumescent paint suppliers gather data for the entire duration of furnace tests so extracting the relevant information for a non-15-min grade simply involves additional computer processing.

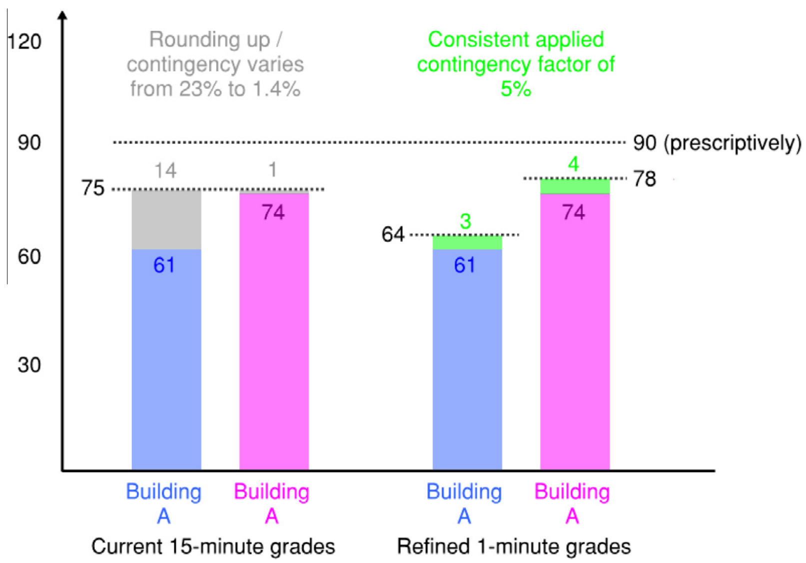

Figure 2. Chart showing a comparison of the respective design fire resistance periods obtained using the current 15-min increment system and a refined 1-min increment system.

- Industry groups behind construction materials other than steel, such as concrete and timber, may claim that refined fire resistance grades would not benefit their fire protection solutions to the same extent. That may be true, but with the benefits that refined ratings would bring for design reliability, transparency and efficiency, the authors believe the change should be pursued independent of construction material regardless. Nonetheless, with interpolation of concrete cover requirements or timber section sizes between the current fire resistance increments, it may still be possible to deliver safer and more efficient structures.
- As noted previously, the approvals process should be enhanced not hindered by a move to more refined ratings. Instead of the safety, cost or even feasibility of a building being potentially determined by the results of an engineering assessment alone and / or the authority having jurisdiction's decision, due to the significant implications of traversing the current 15-min increments, refined ratings would mean that the focus of the approver's review as well as discussions between designer and approver could be on the analysis itself. This will have the added benefit of facilitating the increased interrogation of performance-based structural fire engineering by approvers that is required in order to ensure fire safety in the face of the ever-evolving construction industry.
- Contractors, fire protection suppliers, applicators and others involved in the delivery of fire protection solutions on site may view refined ratings as overly complex to implement reliably. However, this paper does not necessarily propose that individual elements are each provided with different fire resistance ratings, although there are methodologies through which such an approach could be applied [14]. The general recommendation is that an overall building's fire resistance could be specified to finer increments than 15-min, which if planned appropriately, should not prove unduly challenging to implement.

There are likely other reasons that could be put forward in opposition. This paper is intended to stimulate discussion and the authors would therefore welcome feedback and discussion.

The question the fire safety community needs to ask is whether the benefits of safer, more examinable, and more efficient fire resistance design outweigh the changes required?

An opportunity to make the process better

In considering how the design procedure for structural fire resistance may be improved, this paper identifies that the 15-min incremental grades upon which performance are based represent a factor of crudeness that undermines the entire process and proliferates to inconsistencies in the designed standards of safety.

A number of concerns arise from rounding-up fire engineering analysis output to the nearest 15-min grade, primarily:

- Inconsistent levels of contingency and, as a result, standards of safety.
- Undue scepticism and prejudice from approvers, clients and design teams as to the merits of engineering solutions that propose deviations from prescriptive guidelines.
- Inefficient design.

This study presents and compares example buildings that highlight the above shortcomings in the current grade structure and show how a applying a "consistency of crudeness" in the design method, through the use of refined fire resistance ratings, leads to more robust and dependable outputs. Refined grades would also reduce the significance of movement between notional thresholds or "magic numbers" and, therefore, the focus of design and approvals discussions regarding performance-based methods could move away from comparing the outputs of the engineering analysis with the prescriptive guidelines, and towards the validity of the methodology, assumptions, input parameters and other facets of the design.

With the design of more and more "uncommon" buildings that do not fit within the realms of prescriptive guidance, the application and integration of structural fire engineering is becoming increasingly critical in delivering structures that meet life safety and property protection goals. Although still an evolving discipline, modern structural fire engineering can incorporate risk-based and performance-based methodologies that seek to establish the appropriate fire resistance for a building to the minute based on the fire risks and consequences present, and has the capacity to incorporate a wide range of inputs, such as contingency factors, in order to meet particular project, regulatory or stakeholder objectives. A refined rating system would maximise the benefits of such a holistic approach, help promote its application by designers, incentivise future advancement in our understanding of structural behaviour in fire and facilitate the interrogation necessary by approvers and the wider fire safety community of the means by which structural stability is safeguarded in fire.

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References

[1] Post War Building Studies No. 20 – Fire grading of buildings, Part 1 – General principles and structural precautions. Fire Grading Committee of the Building Research Board of the Department of Scientific and Industrial Research, and of the Fire Officers' Committee; 1946.

[2] British Standards. BS 476-20:1987 Fire tests on building materials and structures – Part 20: Method for determination of the fire resistance of elements of construction (general principles). BSI; 1987.
[3] Hopkin D, O'Loughlin E, Kotsovinos P, Wilkinson P. Fire resistance: structural design for fire safety. International Fire Professional, The Institution of Fire Engineers; 2014. Issue No. 10.
[4] Law M, Beever P. Magic numbers and golden rules, fire safety science. Proceedings of the fourth international symposium, International Association for Fire Safety Science 1995:79–84.
[5] Hopkin D, O'Loughlin E, Kotsovinos P, Bisby L. Fire resistance: prescriptive guidance as a panacea? The Building Engineer, Chartered Association of Building Engineers, December 2014 2014:20–2.
[6] British Standards. BS 9999:2008 Code of Practice for fire safety in the design, management and use of buildings. BSI; 2008.
[7] HM Government. Approved Document to the Building Regulations 2010, Part B, Fire safety – volume 2, Buildings other than dwellinghouses; 2013.
[8] Kirby BR et al. A new approach to specifying fire resistance periods. Struct Eng 2004;84:19.
[9] Law A et al. A risk-based framework for time equivalence and fire resistance. Fire Technol 2014.
[10] Elms D. The principle of consistent crudeness. Proceedings of the NSF workshop on civil engineering applications of fuzzy sets 1985:35–44.
[11] Buchanan A. The challenges of predicting structural performances in fires. Fire Saf Sci 2009;9:79–90.
[12] International Standards Organisation. ISO 834–1:1999 Fire resistance tests – elements of building construction. General Requirements; 1999.
[13] American Society for Testing and Materials. ASTM E119–00a Standard test methods for fire tests of building construction and materials.
[14] Bisby L, Gales J, Maluk C. A contemporary review of large-scale non-standard structural fire testing. Fire Sci Rev 2013;2(1):27.
[15] Block F, Butterworth N. The definition of fire resistance requirements for stadium and arena developments based on risk. Steel Struct 2009;9:39–46.
[16] Bailey C, Moore D. The structural behaviour of steel frames with composite floor slabs subject to fire: Part 2: Design. Struct Eng 2000;78(11):28–33.
[17] Burgess IW, Huang Z, Plank RJ. VULCAN – a program for the structural analysis of steel, composite and reinforced concrete building structures in fire. Background and validation. University of Sheffield; 2002.