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SEGMENTATION OF ANALYSIS/DESIGN LEVELS FOR STRUCTURAL FIRE ENGINEERING

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ABSTRACT

Various levels/types of analysis and design methods for structural fire engineering exist, similar to those in other areas of structural engineering (seismic and wind) and in construction material design resistance. These differences entail distinct idealization assumptions, limitations, degrees of complexity, advantages and disadvantages, and applicability to certain classes of problems. Hence, the structural fire engineering methods can range from the simple derivatives of standard fire test results and prescriptive ratings to the most advanced, nonlinear finite element analyses of an entire structural frame subjected to localized natural fire. The selection of the analysis/design approach could influence its results and conclusions.

Current building codes and standards cite certain structural fire engineering methods in an indirect manner, with most emphasis on the easiest and traditional prescriptive methods. A more complete and transparent segmentation of the full spectrum of analysis/design alternatives is desirable to enable further progress in performance-based structural (PBD) fire design, through better identification of the inherent assumptions and limitations of each approach. This paper presents a classification system for structural fire engineering work, highlighting the key constituent factors and variables for any construction material. Major gaps in structural fire design are identified as research needs. This hierarchy is expected to be of practical value to researchers, practitioners, standards developers, regulators, owners, and the public in more explicitly identifying the relative suitability of alternative approaches to the solution of fire design problems.

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1. INTRODUCTION

Standard fire tests, prescriptive building code ratings and their convenient empirical correlations represent the base level of general knowledge in the field from which better design accuracy and applicability can be attained with more refined, higher-level engineering. The latter has become also generically identified as performance-based design (PBD). However, it should be clearly recognized that there is not one PBD approach, but rather different hierarchies of engineering refinement that can be attained within this advanced PBD domain. This paper overviews the non-prescriptive fire engineering methods and highlights their pertinent similarities and differences.

2. GENERAL SEGMENTATION LEVELS FOR PBD

As with other types of analyses and design, structural fire engineering can be addressed at various levels of sophistication. The associated engineering costs and time are usually directly proportional to the level of refinement employed. Figure 1 accordingly illustrates 4 groupings of advanced structural fire engineering alternatives, their estimated improvements in solution accuracy and the commensurate expense of increased engineering effort and complexity. Since the fundamental base layer of standard fire resistance ratings (prescriptive design) is considered to be generally conservative, more refined design will often result in savings of fire protection costs, or at least a rational re-allocation of the available project budget among the various passive and active fire safety measures. Sometimes, the nature of the building project is beyond the scope of the elementary code provisions (such as exposed steel members in required protected construction), and the only recourse is a more advanced analysis. Its project value will depend on fire protection material savings and/or other fire safety enhancements compared to the additional engineering costs incurred. Thus, the incentive for transcending the minimum criteria of the prescriptive code can be economic, functional, or both.

A thermal-only analysis for a natural/real fire, in place of the standard ASTM E119 or ISO 834 exposure, with critical material temperature limits could provide a marginally better solution with only potentially slightly more work. However, because the important loading and structural response features are not included in such, it is a solution of rather marginal value. The four remaining advanced engineering options relate to the breadth of the structural model used in determining if any failure(s) will occur under load during a fire:

1. single member
2. subassembly
3. frame-initial failure
4. frame-progressive failure

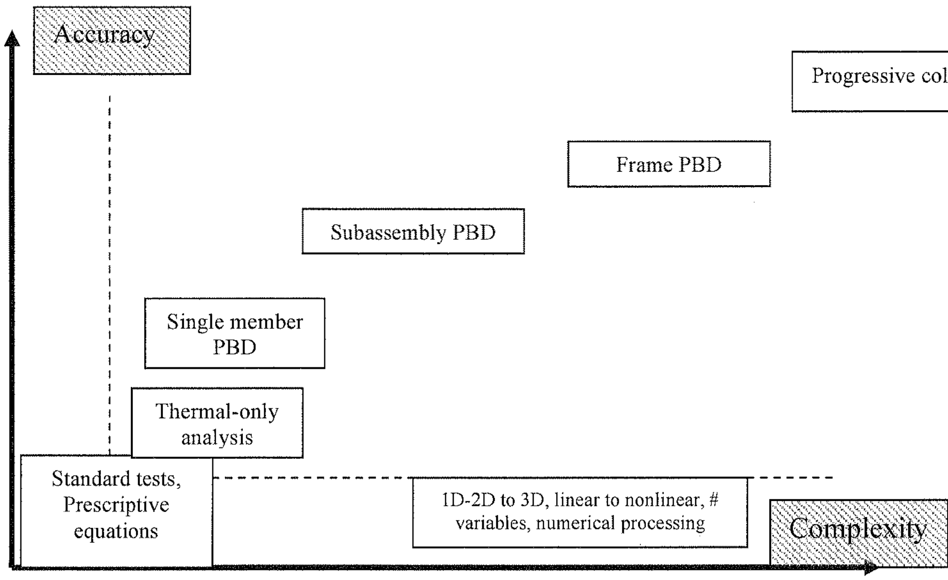

Figure 1 Advanced Structural Fire Engineering Alternatives

The primary objective of structural fire resistance design is to avoid collapse during a fire exposure. Collapse can be broadly classified as either local or global. Local collapse is failure of a single member, connection, or limited frame subassembly, while global or progressive (disproportionate) collapse produces a major cascading series of related failures triggered by the original local failure. The latter is the much more dangerous and destructive in terms of both public safety and property loss. Use of the single member, sub assemblage, or full frame structural/fire analyses will idnetify the source and type of any initial failure. Ordinarily, avoidance of this first structural limit state will suffice for compliance with the minimum safety requirements of the building codes. This is often referred to as member-based or element-by-element design. However, with more recent concerns about terrorist attacks, there is an increased awareness of the risks of disproportionate collapse, particularly for taller monumental buildings and other critical facilities. As subsequently discussed, progressive failure analysis is yet not well developed or established for common structural design applications.

3. CHARACTERIZATION OF ALTERNATIVES

It is important to not only be aware of the different levels of advanced structure fire resistance, but to also understand what each embodies in terms of solution benefits and limitations, and of the expected complexity of the undertaking. Analogous to structural analysis/design at ambient conditions, PBD must provide not only for the primary collapse prevention objective, but also suitable performance/serviceability. The latter limit state under fire exposures should assess affects of the following for purposes of fire containment, if they are not directly included in the model:

- deflections,
- wall or floor slab cracking,
- separation openings or
- fire protection fall-off/damage
- other damage, and
- temperatures on unexposed surfaces

A flow-chart of the PBD process, as illustrated in Figure 2, will frequently be iterative, both for redesign to prevent collapse and for situations when the modeling results are inconsistent with its initial assumptions (eg, fire compartment boundaries are likely to be breached or expected protection damage will alter structural response).

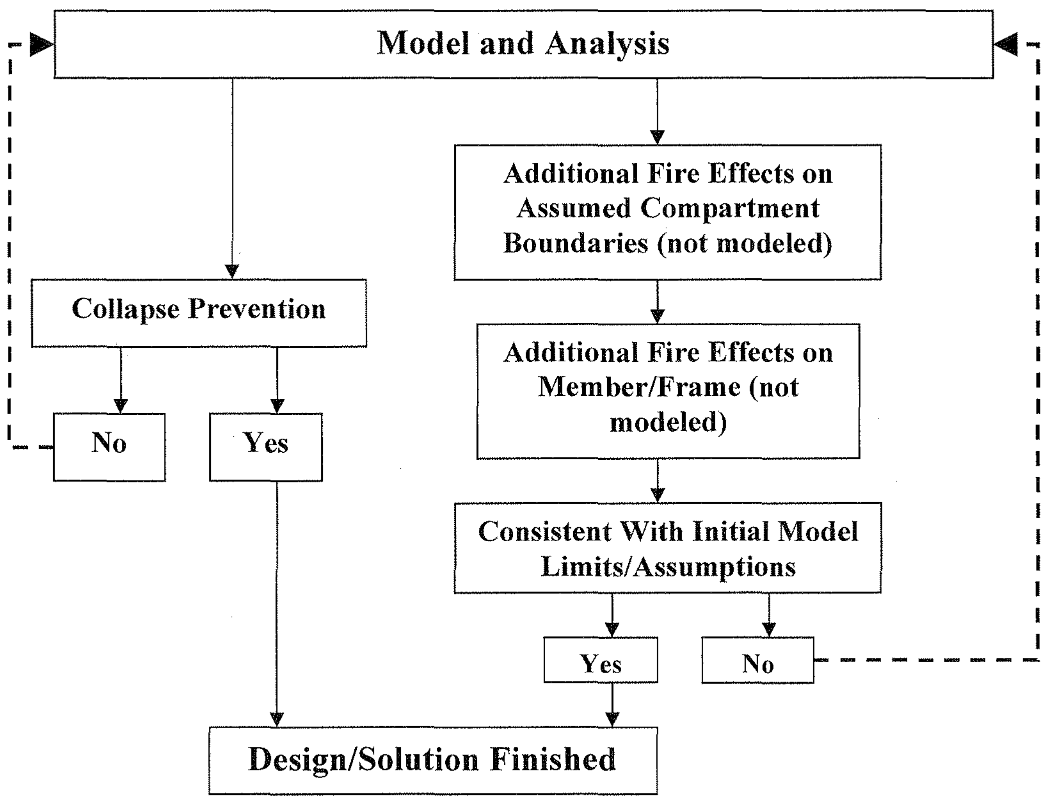

Figure 2 Fire Engineering Objectives and Process

Tables 1a and 1b summarize the key attributes of the single member, subassembly, and full-frame alternatives. The key characteristics are considered to be the

1. fire exposure
    a. standard fire curve (ASTM E119 or ISO 834)
    b. natural/real fire
        i. parametric curve
        ii. zone
        iii. CFD

2. model boundary conditions (thermal restraint)
3. thermal strain formulation
4. connection fire response model
5. heat transfer idealization
6. member, or framing system, ultimate strength
7. deflection/damage/thermal assessment

A rational assessment of these seven characteristics can estimate the relative positioning of each alternative in Figure 1, using the prescriptive, standard fire resistance ratings as the baseline in the two-dimensional space of accuracy and complexity. In R&D, robustness and accuracy of the analytical simulation is often the principle single constraint. However, the fiscal and scheduling realities of engineering practice must regularly balance trade-offs between potential design benefits of additional refinements and their costs. The relative merits for selection of a particular approach within this context will be greatly project dependent. The more advanced techniques will be driven by special needs.

Table 1a Key Characteristics of Single Member Analysis

Compartment Fire-*Single Member* Analysis		
Fire		
Standard (E119 or ISO834)	Natural	
	Parametric Curves	Simulation Models – zone or CFD
Thermal Restraint – none or approx.		
Thermal Strains – none or approx.		
Connection fire response effects – none or grossly idealized		
Heat Transfer		
1D (lumped mass)	2D	3D
Concurrent Loads [1,2]		
Max. Design		Expected Load Combination
Member Strength		
Temperature-modified normal design provisions		Other rational mechanistic model
Integrity Assessment		
Determine safety or ultimate failure mode of member		
Performance Assessment		
Did large deflection/distortion lead to breach of adjacent fire barrier(s) or other induced failure(s) ? And/or check standard test limits.		

[1] If no applied loads are assumed, maximum temperature solution attained does not require any further structural analysis
[2] Load effects on given member determined from usual ambient structural analysis

While the fire modeling side of this problem is only peripherally addressed in this presentation, one basic recommendation in this regard is made. The imposed fire exposure can range from a standard fire curve to the most sophisticated CFD simulation of a natural fire. It would typically be greatly incongruent and of no technical solution benefit to pair the most simple fire or structural model with its most advanced counterpart for a given problem, as illustrated in Figure 3. The refinement level of the fire model

Table 1b Key Characteristics of More Advanced Analyses

Single/Multiple Compartment Fires- *Subassembly or Full Frame* Analysis					
Fire					
Standard (E119)		Natural			
		Parametric Curves		Simulation Models – zone or CFD	
Thermal Restraint – included					
Thermal Strains – included					
Connection fire response effects – modeled					
Heat Transfer					
1D (lumped mass)		2D *		3D *	
Concurrent Loads [1]					
Max. Design				Expected Load Combination *	
Structural Analysis					
Linear elastic		2^{nd} order elastic *		Fully nonlinear (geometry and material) *	
No stability effects		Elastic member/frame buckling		Elastic and inelastic buckling: local, member, and frame	
2D	3D	2D	3D	2D	3D
Member Strength					
Temperature-modified normal design provisions		Temperature-modified normal design provisions		Directly computed	
Integrity Assessment					
Determine safety or initial structural failure mode					
					Continue thru possible progressive failure mechanisms
Deflection/Damage/Thermal Check					
Did deflections cause any additional damage and fire spread consequences beyond those directly modeled? (fire barrier cracking, openings, etc., temperatures on unexposed surfaces)					

[1] If no applied loads are assumed, maximum temperature solution attained has no need for further structural analysis

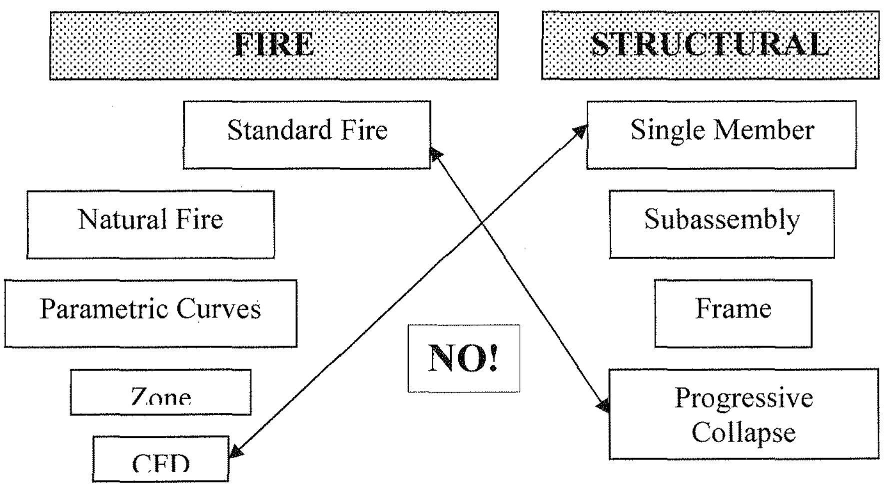

Figure 3 Matched Refinement of Fire and Structural Models

should be similar to that of the structural for overall consistency of the problem idealization.

4. KEY STRUCTURAL MECHANISMS FOR ADVANCED ANALYSES

Table 1b lists several modeling/response attributes possible for the more advanced structural-fire solutions. Unless one performs the most intricate 3-D, highly discretized and nonlinear analysis, some degree of modeling simplification with assumptions will normally be advantageous. The highest analysis level will ordinarily be employed only in research or forensic studies of major events. In design practice, the relative importance and prudent selection of the PBD method should be heuristically guided by the scope of the particular project and nature of expected results. Past experience and knowledge in the field will be extremely useful in reducing large complex problems to much more manageable proportions. However, if an important performance attribute is ignored or incorrectly modeled, the final analysis results could be substantially erroneous. The following sections conceptually outline several such higher-order considerations:

4.1 Thermal Strains/Restraint

Often, an essential element for the fidelity of a structural-fire model is adequate representation of the thermally-induced strains and forces, particularly in the floors, and their affects on the frame. Two recent papers [1,2] on analyses of the 9/11 World Trade Center (WTC) collapses and the NIST 2005 Report[3] have demonstrated the great importance of properly including this behaviour, that is usually not considered under ambient conditions. Deflections of floors with reduced heat-affected stiffness will arise from both the existing vertical loads and thermal gradients (bowing). Furthermore, the expansion restraint of the heated floor by the adjacent columns will induce compression and incremental curvatures, as shown in Figure 4. These high temperature affects will not only reduce the strength of the horizontal members acting as beam-columns, but more critically, the overall stability of the main building columns for which they provide lateral bracing. These columns, due to the horizontal displacements/flexibility and sag of the fire floor(s), now have longer unbraced lengths, along with new demands for floor reaction support, that reduce their strength for carrying the other imposed superstructure loads. A frame or subassembly model would be necessary to explicitly capture this type of behaviour. More discussion of these WTC and other advanced studies is provided subsequently.

4.2 Catenary Action

A floor slab and beam may change from pure bending resistance at ambient temperatures to combined bending and axial compression due to restraint of thermally-induced expansion; finally, after further thermally-induced bowing to produce the large vertical deflection during the high temperature stages of a fire exposure, it will experience the combined bending and axial tension mechanism (catenary or membrane action). This redistribution of the load-carrying capabilities of a typical steel-concrete composite floor system in a building from simple flexure under service conditions to catenary action at ultimate is schematically illustrated in Figure 5. This floor mechanism is naturally related to the thermal expansion affects discussed previously. As vividly demonstrated in the Cardington research, catenary action of a floor system can provide additional reserve strength beyond its primary bending resistance, if its cross-section, end connections and boundary conditions are amenable to formation of this mechanism. Ordinarily, special formulation provisions must be included to capture this response mode in a single member or subassembly-type solutions.[4]

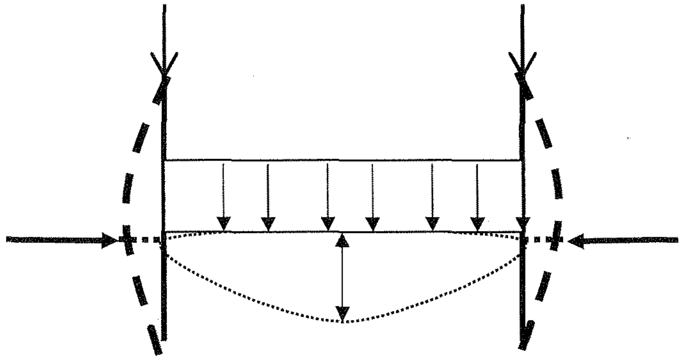

Figure 4 Affects of Floor Thermal Expansion on Columns

4.3 Progressive Failure

Most of the structural-fire analyses are considered to be static in nature, unless dynamic affects of blast, impact or seismic actions are involved. Static problems usually enable relatively easier solutions. However, the analytical determination of whether an initial local/member failure can propagate to further global or disproportionate structural instabilities may be difficult, or impossible, for most finite element software operating in a static analysis mode. Numerical solution convergence for any subsequent catastrophic and complex global collapse mechanisms can be much more easily achieved if the nonlinear software processes the analysis (with resulting large deformations, member failures, singularities, etc.) as a dynamic, rather than static equilibrium problem, with an appropriate time step. [5]

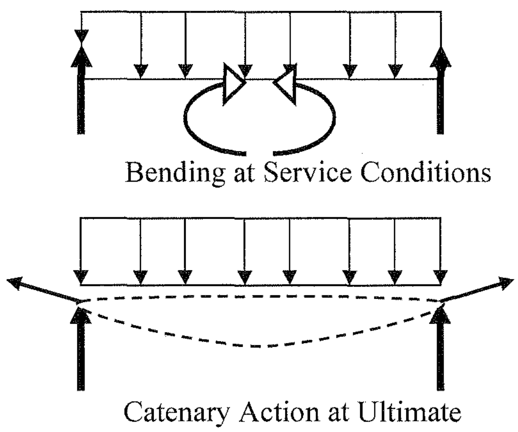

Figure 5 Changes in Structural Resistance of Floor Beams
From Primary Bending to Catenary Action

In addition, it may be necessary to conduct such simulations in full three-dimensional space, with adequate and appropriate discretization of the potentially affected members, i.e. many more model nodes and elements, to reach the best response fidelity. Such intricate simulations will require extensive computing resources, expertise, time and effort to accomplish. More research on progressive collapse is needed. At the current time, most structural design problems do not mandate consideration of such global failure.

5. COMPARATIVE REVIEW OF SELECTED AVANCED STUDIES

Since the 9-11 tragedies, much work, many papers and reports have been written to explain how the WTC collapses happened and their causes. The references cited earlier[1,2,3] and four other papers[4,6,7,8] provide further insights into several advanced modelling perspectives, and the requisite engineering judgment to simulate a complicated failure under fire exposures. The Table 2 summary shows that the analytical results and conclusions can vary, depending on the assumptions and methods employed.

Table 2 Summary of Selected Advanced Studies

Reference	Building	Fire Model	Structural Model	Results
6	WTC	Parametric	Single member (floor truss)	Effects of protection thickness - floor failure initiated collapse
8	Multi-story steel frame (One Meridian Plaza)	Parametric	2-D subassembly, nonlinear, w/floor beams or slab	Effects of horizontal expansion at floor beams on columns
1	WTC	Parametric	2-D subassembly, nonlinear	Perimeter column collapse due to floor truss failure
2	Parking garage	Temperatures from full-scale fire test	3-D, nonlinear	Validation with test results, demonstrate column response to horizontal slab expansion and vertical deflections
7	WTC	special	3-D, non-linear	Simulate damage, core and perimeter column collapses
3	WTC	CFD	3-D, fully nonlinear	Simulate damage & perimeter column collapses
4	Steel floor system (Cardington)	empirical	subassembly	Catenary action strength mechanism

6. RESEARCH NEEDS

Some future research needs to help enhance this practical application framework for fire PBD are:

- further experimental validation of models
- calibration/validation of simpler models by means of the more advanced ones
- better understanding of progressive collapse and its mitigation
    i. fire and structural effects that breach compartment walls to facilitate horizontal fire spread
    ii. fire and structural effects that breach horizontal separations to facilitate vertical fire spread
    iii. fire effects on damaged structures (terrorist or seismic)
    iv. real-time predictions to guide emergency evacuations

7. CONCLUSIONS

Several distinct choices for analytical models are possible for a variety of structural-fire interaction problems. Expertise and good engineering judgment are invaluable to selection of the best PBD approach for a given technical issue within the context of a particular construction, forensic, or research Project. This paper outlined the various alternatives available for this type of structural modelling, along with their limitations, which should provide a helpful guidepost to general practitioners and regulatory building officials who are not intimately familiar with these subjects.

The prevalent time and budget constraints of Projects will often preclude regular application of the most advanced fire PBD approaches in practice. Thus, the simple or intermediate complexity models are expected to be generally favored. However, the inherent assumptions and limitations of such solutions must be duly recognized. Since the analytical results can differ with modelling approach and assumptions employed, it is important to use the appropriate level of refinement for the given project objective(s). Much like standard fire tests of limited size assemblies, single member or subassembly models are incapable of resolving broader frame interaction and stability issues.

The greatest practical benefit of the most advanced, nonlinear, 3-D solutions, in combination with suitable experimental and actual performance data, is to broaden understanding of the collapse phenomena involved, further validate and serve as calibrations tools for the simpler methods that will be the most frequently used. In some form, they could also eventually serve as real-time predictors of the severity of a given ongoing structural-fire event relative to building evacuations.

8. REFERENCES

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