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FIRE MODELING TOOLS FOR FSE: ARE THEY GOOD ENOUGH?

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SUMMARY

Performance-based building codes presume the existence of models which can predict necessary fire scenarios. The author examines today's state-of-the-art zone fire models and finds that many crucial aspects of fire physics and chemistry are not included in these models. Six specific limitations are discussed. These limitations are commonly overcome in fire reconstruction and litigation when large-scale tests are commissioned. Since such testing will normally not be affordable for the design process, it is essential that the gaps be filled. The gaps are seen to be partly due to funding limitations within the research organizations. Thus, it is suggested that cooperative research may be the best strategy.

BACKGROUND: PERFORMANCE-BASED BUILDING CODES

During the last decade, a great deal of interest has focused on "performance-based" building codes. This is contrasted to a conventional approach which is *prescriptive*. Under prescriptive building codes, actual widths, lengths, strengths, thicknesses, etc. are prescribed, as are necessary equipment and features for safety. Our existing building codes are not, of course, 100 percent prescriptive. It can be argued that, for instance, fire endurance requirements, when referred to the ASTM E 119 test[1] are actually performance-based, since the test simulates real-fire conditions to some extent. Be that as it may, the successes of fire safety engineering (FSE) over the last two decades have enabled the notion to be considered of genuinely performance-based building codes, at least in the fire safety area.

Recently, some discussion has been made as to what is actually fire *performance*. The view has been put forth[2] that the only rational basis of performance is a risk statement, which would run something on the order of: "by entering this building you are assuming a risk of x fatalities per year of exposure." Wholly probabilistic formulations of fire performance have, in fact, been put forth[3]. These suffer from the limitation that the probabilities necessary to assess building fire risk are unavailable except in some very limited cases[4]. In turn, wholly-probabilistic building design is still a long way off. What is being considered for the near future could, more appropriately, be termed *FSE-based* design. This definition leaves somewhat unspecified the exact objective or evaluation criteria for approving a building design; these can be worked out rationally on some deterministic basis. What the definition does specify is the *tools* which shall be used. It says that the fire response of the building and the people is to be *calculated*, rather than *prescribed.*

A number of countries have already defined strategies for producing such an FSE-based building code. These include New Zealand, Australia, Canada, the UK, the Nordic countries, and Japan. Even more generally, the International Organization for Standardization (ISO) has had a subcommittee, ISO TC92/SC4, which has been working for more than five years now in order to define some general FSE principles suitable for such building codes.

Already a number of detailed references have been published[5,6,7], and the whole procedure of FSE-based design has even been described as being easy to do[8].

However, it is not at all obvious that the procedures of today are easy to do; even more important, serious questions exist whether they are up to doing the job at all. Indeed, it must be emphasized that: *All of the FSE-based approaches presume our routine capability to numerically predict fire behavior.* In other words, they assume that adequate fire modeling capability is available to design professionals (or can shortly be made available). This latter point is of significant concern and is the topic of this paper.

FIRE MODELING DEVELOPMENTS

An FSE approach to building design requires that numerous aspects of building fire safety be computed, including, for instance, evacuations, fire department actions, etc. Many of these topics are indeed highly specialized and lacking in any generally agreed-to tools. The most basic feature of building fire performance, however, is the computation of the *fire itself*. This is the starting place for any further design efforts; without knowledge of the expected fire, there can be little success in designing fire protection features in a rational, engineered way. Thus, we consider here only that aspect of fire modeling which pertains to predicting the basic fire behaviors in rooms of buildings.

The first theoretical underpinnings of room fire modeling were created by the late Prof. Kawagoe at the Building Research Institute of Japan during the 1960s[9]. The first computer fire model actually released to the public was from Prof. Sven-Erik Magnusson of Lund University in 1973. The first fire model to be released in the U.S. was from the present author[10]. The latter, COMPF, was limited to treating only a post-flashover fire in a single compartment. The next major leap was the development of the idea of the plume as the driving force for the fire within the compartment. This idea was first presented by John Rockett[11]. The first fire model to treat the pre-flashover fire regime was the Harvard Fire Code CFC, developed by Prof. Howard Emmons and Henri Mitler[12]. Eventually, some scores of fire models were developed, as summarized by Friedman in his survey[13].

During the early 1980s, the fire models were still viewed as works-in-progress, as promising but clearly incomplete. By the late 1980s, the situation had changed. Fire modelers were becoming comfortable with their offerings, and tools were being viewed as ready for use. Perhaps the landmark event on this time scale was the release of HAZARD I from NIST in 1989[14]. Since then, the assumption has been made in all of the FSE work that fire models *are* available which are complete enough and adequate to predict desired fire situations. Yet, this is far from being true, as of today. The models in current use do many things very well. They include features such as capability for treating 15 rooms, gas flow through both vertical and horizontal vents, forced ventilation, and other features which would have been just a gleam in the developer's eye a few years earlier.

So there is clearly a solid basis of expertise and very significant achievements which are at the base of our fire models. Yet, there are also many extremely frustrating limitations, to the point that claiming that fire models are ready for FSE use may significantly overstate the actual capability. These limitations need to be seriously addressed and rapidly removed. We now wish to outline some of the salient issues which we feel must be solved.

LIMITATIONS OF FIRE PHYSICS AND CHEMISTRY

The fire models of today have some limitations due to lack of some aspects of user friendliness, occasional bugs in programs, and similar operational difficulties. The most serious limitations, however, come from the fact that essential items of fire physics and chemistry are missing from even the best of the existing models. Some models, of course, will always be less evolved than others. What we wish to look at, however, are features which are missing from *all* of the released, publicly available fire models. The following limitations are seen as being the most problematic.

No Flame Spread

Not a single available room fire model today offers flame spread calculations. Flame spread needs to be considered in any fire where combustible solids are present and can ignite and spread flame. This excludes certain classes of industrial and offshore fires, but includes almost all others. Theories of flame spread, of course, do exist, and a number of them have been published in the literature. None of them, however, are incorporated in the available fire models. This, perhaps, is the single most serious limitation of today's models. (Some *correlations* have been proposed for predicting flame spread, but these do not meet the minimum criterion to qualify as *fire models,* to wit, they are so empirical that the fundamental conservation equation—heat balance—is not incorporated in them.)

No Heat Release Rate

Heat release rate is the single most important variable in describing fire hazard[15]. All of today's advanced fire models* treat heat release rate by simply asking the user to supply input values of HRR and then using those. This, of course, is bookkeeping and not fire physics. Real fire physics will require that the instantaneously burning area be computed. Using this, bench-scale (per-unit-area) HRR values can then be used to predict the real-scale HRR. But to predict the burning area requires that a flame spread model be available, and it is not. With some of our simpler fire models, the situation can be even more misleading. Such models commonly specify t^2 fires, instead of demanding actual HRR. These idealized fires have almost no connection with reality (see Appendix).

No Fire Chemistry, Especially CO

It has been comprehensively demonstrated that carbon monoxide is the most important combustion product in determining fire toxicity[16]. A number of today's fire models treat the CO issue by asking for benchscale data on CO yields to be inputted; the CO yield for the real-scale fire is then assumed to be identical to that from the bench-scale test. This is known to be an inadequate strategy[17]. Furthermore, a first-order theory for CO prediction exists and has been shown to be applicable to a number of problems of significant practical interest[18]. Surprisingly, it has only shown up in one Japanese model, although to include it would not seem difficult. Even for the basic production of CO, furthermore, there are already cases known where we would like to go beyond the first-order theory. These include cellulosic-material burning ceilings[19], stagnant air connected-spaces[20], and the incineration or non-incineration of CO in the doorway plume. These latter are very important practical situations which cannot even be contemplated for the insertion into room fire models since the chemistry of these conditions has not yet been quantified. Curiously, a model for HCl losses *is* available[21,22], but it is the only piece of chemistry potentially useful to engineers which has been made available to them. It is, of course, of relevance only for PVC and the few other chlorine-containing combustibles. Interestingly, there appear to be no reports of its usage apart from the development team.

No Smoke Chemistry

A number of the fire models claim to treat smoke. They do this by asking for input of smoke yields from a bench-scale test. The real-scale smoke yield is then assumed to be identical. In other words, it is assumed that there is *no* chemistry involved in smoke production. Assuming smoke yield to be independent of scale or burning conditions

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* A few models attempt a very simple calculation, e.g., for a liquid pool or a wood crib.

is not as rash an assumption as for CO and under certain conditions this is reasonable[23]. However, under other circumstances it is not[24]. Here the basic problem is that no simple computational model for smoke chemistry has been put forth, so obviously it cannot be put into room fire models.

Absence of Realistic Layer Mixing

The two-layer simplification used by a majority of today's fire models is a very powerful one and one which is largely realistic. Since, prior to flashover, the occupants are generally in the lower layer, it is very important to be able to determine their tenability from a combustion gas point of view. This cannot be done at the present since adequate mechanisms are not incorporated in the fire models which would simulate the vitiation of the lower layer with combustion products. This is partly due to a shortage of experimental data: there are very few good validation experiments where extensive gas probing of the lower layer has been made.

No Suppression

Automatic fire extinguishing systems are becoming increasingly common in various occupancies, and fire simulations today should be able to incorporate the effects of both automatic sprinklers and, possibly, of manual firefighting. Only one fire model has been described[25] which includes fire suppression. However, that model is proprietary and, apart from the suppression equations, its fire physics are very primitive, so it has not received any significant usage as a fire model.

The above list of limitations is quite sobering. It clearly indicates that, today, fire models can be used in FSE-based design under some specialized circumstances only, and not for general design problems.

FIRE MODELING SUCCESSES

From the above situation, one might hasten to conclude that fire models are not useful. Such would be an unwarranted generalization. Fire modeling, even in its current imperfect state, is finding daily applications. However, the successful applications are almost entirely in the field of fire litigation and reconstruction of fire incidents. Why, then, is fire modeling a success in litigation, but is not yet ready to use in building design? There are two main reasons for this:

1. In fire litigations, if the case is important, world-class fire scientists are retained to essentially "create" new aspects of fire science. For example, one of the earliest major-loss fires receiving such attention was at the Beverly Hills Supper Club, where Prof. Howard Emmons was retained to model aspects of the fire[26]. Prof. Emmons was at the time regarded as the pre-eminent fire scientist in the world. Another example is the handful of fires which were modeled by H. E. Nelson and associates at NIST[27,28]. These analyses made use of numerous NIST fire scientists. Such scientific resources are simply not available to architects and engineers engaged in the normal process of building design.

2. In fire litigation, cost restraints are relatively secondary. Thus, in those cases where techniques do not exist for predicting large-scale behavior on the basis of bench-scale tests, actual large-scale fire tests are commonly commissioned. Such testing programs are financially simply out of reach of any but the most extraordinary design projects.

We can see from both these considerations that the fire litigation environment is very different from the case of building design. It is clearly not reasonable to expect that the architect or engineer using a performance-based building code will retain one of the world-class fire scientists for an exhaustive research study, nor that he commission full-scale fire tests. In addition, it may be noted that the task required for reconstruction work is relatively simple: only one specific fire is to be quantified. In the design environment, numerous fire scenarios may need to be developed and modeled.

CONCLUSIONS

Performance-based building codes require that computational tools be available for various aspects of fire behavior and of response to fire. At the present, the tools which are presumed to exist are simply unavailable or incapable of doing the job by themselves.

The gaps can be bridged on an *ad hoc* basis by retaining highly specialized fire scientists to provide the needed model components or by commissioning large-scale fire tests. Such schemes are fruitful in fire litigation, but are normally financially precluded in design problems.

The limitations do not exist because model developers are unaware of users' needs. Indeed, some institutions, such as NIST, have invested very serious efforts into understanding and trying to address users' needs. Instead, the problems are due to limitations of funding and resources which have been a concern at most fire research institutions for a number of years. In this light, the solution is also clear: barring any unexpected large jumps in funding, cooperative efforts are necessary. The expertise to address all of the issues discussed here exists collectively in the world's fire research institutions. What is necessary is that institutions with some skills and resources in these areas develop arrangements to cooperate with others in some joint development work. Institutions, such as CIB W14, FORUM, and SFPE, already exist which are possible channels for collaborating on cooperative fire research endeavors. It is essential that they be harnessed to the needs of the designer attempting to do FSE-based designs.

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APPENDIX: THE T^2 FIRE AND ITS TENUOUS RELATION TO REALITY

A number of the simpler models in use worldwide prescribe the fire conditions not by computing the actual HRR curve, nor by asking the user to input such a curve. Instead, they claim that all real fires can be closely matched up to one of four idealized fires. These are called 'slow,' 'medium,' 'fast,' and 'ultrafast.' This approach has now been used for so much engineering work that undoubtedly many practitioners feel that it is soundly based in fire physics. Yet, this is far from the actual reality.

The use of the t^2 fires first arose in the early 1970s, when quantitative performance evaluation of fire detectors was first being attempted[29]. It was noted that the HRR from fires could have different rates of rise and this would affect the response of the detector. Thus, a series of different categories of initial rate of fire growth were set up to aid in such detector studies. This was subsequently popularized when it became part of the standard NFPA 72[30]. It is important to note carefully the original application—characterizing the response of fire detectors. A fire detector should alarm very early in the fire, before it is a threat to any occupants. This level will typically be less than 100 kW. For such small fires, declaring that there are only four distinct fire types is not a bad decision. In fact, the designer of a detector would not know what to do with any greater amount of detail about the fire. But, once the detector designer has provided adequate responsivity for such a small fire, his job is finished; larger fires are not a concern to him. Indeed, we may note that a much larger fire will destroy the detector itself!

Such small fires, however, are not the appropriate focus for modeling the general fire hazard in buildings. Even in structures of very low combustibility, occupant goods can provide fires yielding megawatts, not kilowatts. Yet, the detector designer's four