Room Fire Modeling within a Computer-Aided Design Framework

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ABSTRACT

A framework for the integration of room fire modeling within a computer-aided design (CAD) environment is developed. The framework is comprised of three primary features: a graphic CAD interface, an analysis model and a data base of physical attributes. Key features of CAD systems required to permit the integration of engineering analyses include object-orientation, the association of attributes with objects and the ability to extract attributes from a CAD-developed drawing data base. A quasi-steady zone model for room fire analyses is described briefly. The definitions of objects and their attributes for these room fire analyses are considered. An example implementation of the CAD framework is presented.

KEYWORDS: fire modeling, computer-aided design, fire hazard analysis.

INTRODUCTION

The technology of building design is changing with the development of computers and software suitable for design purposes. This change in technology, commonly called computer-aided design, or CAD, permits the integration of engineering analyses into the building design and documentation process. A framework for the integration of one type of engineering analysis, room fire modeling, within a CAD environment is the topic of this paper.

The CAD framework described here has three primary features:

1. A CAD interface;
2. An analysis model, in this case for room fire analyses;
3. A data base of object attributes or properties.

An overview of the framework and the relationships between elements of the framework are illustrated in Fig. 1. The CAD interface permits drawing to be maintained as the primary method of recording design information. Incorporation of engineering analyses within a CAD framework requires that design be conceived in terms of discrete objects; the selection of objects depends on the analysis to be performed. The framework is developed in terms of a quasi-steady room fire analysis model; objects for this model are developed. These objects have physical as well as geometric attributes that influence the analysis. Hence, a data base of physical object attributes comprises the third feature of the CAD framework.

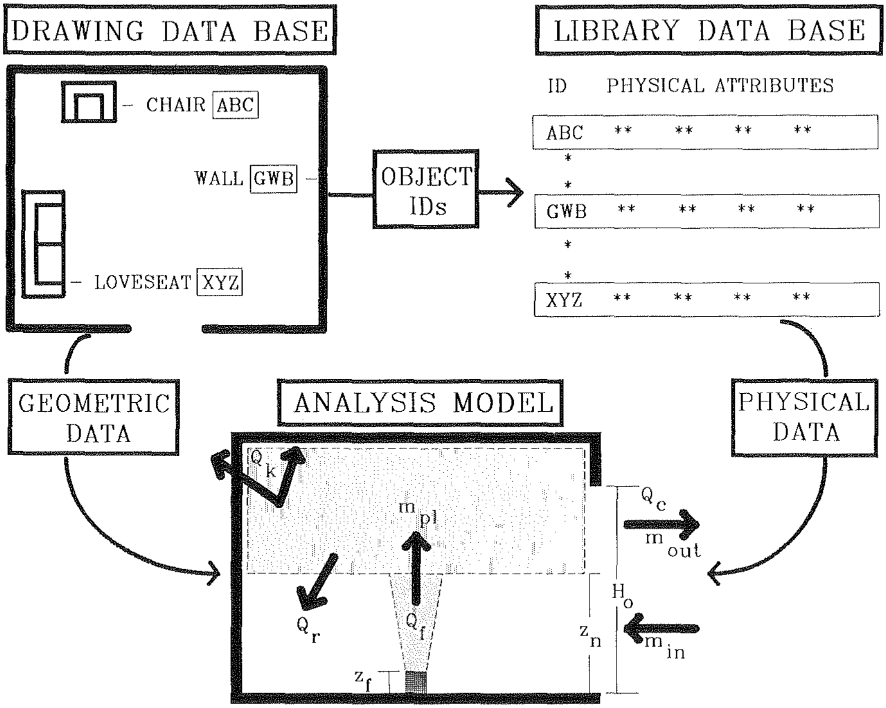


Figure 1: Overview of CAD framework showing relationship between elements.

KEY FEATURES OF CAD SYSTEMS

Drawings in a traditional design context consist simply of lines, arcs and text scribed on paper with pen or pencil. These markings serve as physical models for design; they possess no intrinsic meaning. People must identify and interpret relationships that may exist. Data retrieval from drawings or a project file, such as for cost, structural, environmental or other analysis, must be performed manually.

In a CAD environment, lines, arcs and text can be combined and defined to represent objects and meaning can be associated with the occurrence of objects in drawings. This representation of design elements in symbolic rather than physical terms is known as object-orientation; it is the main distinction between manually developed drawings and computer-based building descriptions. Object-orientation is the key feature that permits the integration of engineering analyses with building design [1,2] because it permits design to be conceived and implemented in terms of meaningful design elements, which can be used for the analysis of performance and functional aspects of design as well as for the spatial modeling generally associated with the building design process.

The concept of object-orientation is illustrated in Fig. 1. The sets of lines used to construct the chair and loveseat shown in the drawing data base in Fig. 1 have no intrinsic meaning if drawn manually. In a CAD environment, these sets of lines can be defined to represent each respective object and the CAD system can recognize the occurrence of such objects in a drawing data base. The CAD system then can extract information regarding objects, such as the number of occurrences and the coordinates of each object, and this extracted data can be used as input to an analysis model.

CAD systems useful for the integration of engineering analyses permit the association of attributes with objects. Attributes are used to define the physical and geometric properties of objects required to perform a desired analysis. While virtually all CAD systems permit the construction of objects from primitive elements and other objects, not all CAD systems currently support the association of attributes with objects [3].

Drawing data bases generated with current microcomputer-based CAD systems are best suited for storing geometric data regarding objects, such as their locations and dimensions. This geometric data then may be extracted from the drawing data base. In general, separate library data bases are more suitable for storing physical attributes of objects. The only non-geometric data that must be assigned and stored in a drawing data base is a key attribute used by the CAD system to uniquely identify each object. The key attribute provides cross-reference to the separate library data bases. This concept is illustrated in Fig. 1.

This arrangement minimizes the non-geometric data storage requirements for a drawing data base and minimizes the data needed at the immediate disposal of the designer during drawing development. This tends to reduce the potential for user input error, but does not eliminate it entirely because the designer still might enter the wrong ID for an object. This practice also has the benefit that any changes or additions to the physical attributes of objects only need to be made within the library data base. If these properties were stored with each occurrence of objects in a drawing data base, then each occurrence would have to be edited to revise the attributes associated with each object.

To summarize, the key features of a CAD system required for the integration of engineering analyses within a CAD framework are:

1. Object-orientation;
2. Association of attributes with objects;
3. Ability to extract attributes.

The definitions of objects and their attributes depend on the analysis to be performed. For different analyses, it is appropriate to utilize descriptions based on different types of elements. For example, a structural analysis might use a description in terms of the structural framework of a building and a thermal performance analysis might employ a description in terms of exterior walls and windows. For the structural analysis, structural member sizes and strengths would be among the appropriate attributes, while for the energy use analysis, thermal properties of the building envelope would be among the necessary attributes. Similarly, objects must be defined for room fire analyses and appropriate fire attributes must be associated with these objects to perform the desired analyses.

DESCRIPTION OF A QUASI-STEADY TWO-LAYER ZONE ROOM FIRE ANALYSIS MODEL

At this point, a quasi-steady two-layer zone fire model that may be used for room fire analyses is considered to elucidate the appropriate definition of objects and their attributes for room fire analyses. This model, described in detail by Mowrer [4], is illustrated schematically in Fig. 1. The model has been implemented on SuperCalc4 [5], a spreadsheet program that runs on IBM PC and compatible microcomputers.

Energy and mass balances on the hot upper layer of a room fire are considered. Energy released by a burning object, Q_f, enters the hot upper layer through a plume rising above the object. The mass of fire gases entering the hot layer through the plume, m_{pl}, is balanced with the mass flow out through openings, m_o. This treatment neglects any mass accumulation or depletion in the layer as well as any mass transfer to the layer other than through the plume. Hence, the distinction that this model is quasi-steady.

Burning objects are distinguished as either furnishings or finishes. Furnishings are discrete objects of fixed initial dimensions. In residential buildings, furnishings include items such as chairs, sofas, beds, desks and wardrobes. In industrial buildings, furnishings might include pieces of machinery and pallets of products. Finishes have dimensions which depend on the room geometry; they include wall, ceiling and floor linings.

The energy released by a fire in a room is lost by three mechanisms: conduction through room boundaries bordering the hot layer, Q_k, radiation to and conduction through lower layer boundaries, Q_r, and convection through openings, Q_c. Design factors that influence these loss terms include the thermal properties and area of the room boundaries and the size, shape and location of room openings. Thus, the description of a building for room fire analyses can be represented as illustrated in Fig. 2. A building is composed of floors, which are composed of rooms. Rooms are composed of four types of objects or elements: boundaries, openings, furnishings and finishes. These are the basic elements that may be used to describe a building for room fire analyses within a CAD framework.

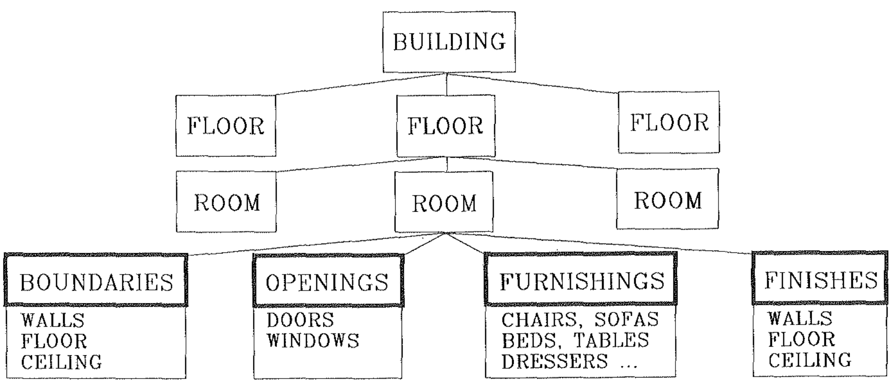


Figure 2: Building description in terms of objects for room fire analyses.

ATTRIBUTES OF OBJECTS FOR THE ROOM FIRE ANALYSIS MODEL

Attributes to be associated with objects may be geometric or physical. Both types of attributes are needed for room fire analyses. Geometric attributes generally are stored internally by CAD systems to represent dimensions of objects in a drawing data base. Physical attributes typically must be defined by the user and, in general, most appropriately are stored in a library data base. The attributes of objects needed for the room fire analysis model are described here. Other fire analyses, such as for smoke production and transport, would require the association of other attributes with objects; the framework would be the same.

The attributes of room boundaries that influence room fire conditions include:

1. Surface area;
2. Thermal conductivity;
3. Density;
4. Heat capacity;
5. Thickness.

These are the attributes to be associated with boundary materials in either a drawing or library data base.

Room openings affect the mass balance and, consequently, the heat balance used to model room fires. The attributes of openings required to permit evaluation of this influence are:

1. Height of opening;
2. Width of opening;
3. Height to bottom of opening.

This treatment assumes that openings are rectangular vertical openings in walls, such as doors and windows. It also assumes at present that the effect of mechanical ventilation may be neglected.

The primary factor influencing the course of room fires is the heat release rate history of furnishings and finishes. The rate of entrainment of air into fire plumes also must be known with reasonable accuracy for room fire analysis models because this term has a direct effect on the energy and mass balances used to describe room fire processes. Good estimates of entrainment rate generally yield good estimates of layer temperature and mass flow in zone room fire models; poor estimates of entrainment rate yield poor estimates of these room fire conditions. The fire attributes of furnishings and finishes needed for the room fire analysis model at present are:

1. Description of heat release rate history;
2. Description of entrainment rate;
3. Height of the fuel object.

The height of the fuel object is required as an attribute because it influences the height over which entrainment occurs. This treatment assumes that an effective fuel height can be assigned to represent vertical fuel objects. A general method to describe entrainment rates for real furnishings and finishes requires considerable further investigation.

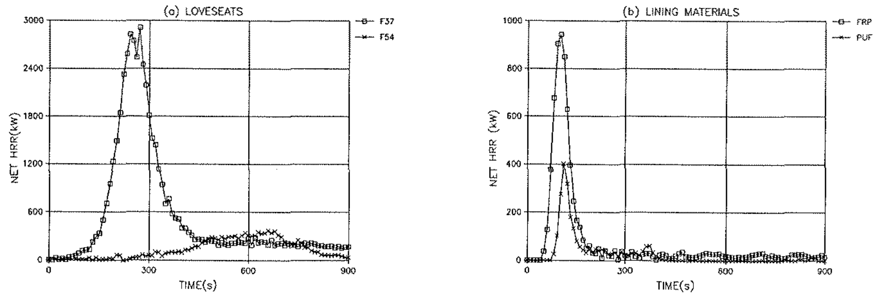


Figure 3: Measured heat release rates for: (a) two loveseats; (b) two wall lining materials.

CHARACTERIZATION OF HEAT RELEASE RATE HISTORIES

Recognition of the importance of heat release rate in room fires has led to the measurement of heat release rate histories for many furnishings and finishes. Such measurements have been made feasible by the development of the oxygen consumption technique for the determination of heat release rates [6,7]. Measured heat release rate histories for two loveseats [8,9] are illustrated in Fig. 3a and for two wall lining materials [10] in Fig. 3b. Measurements were recorded digitally. These digital records of time-heat release rate data couples could be associated as attributes with these objects; however, this requires a large amount of data storage. Therefore, analytical characterizations of the heat release rate histories of objects have been developed.

The heat release rate histories for a number of furnishings and finishes have been characterized with t^2 curves [4]. These representations include characterization of the decay portion of heat release rate curves due to fuel burn out. Such characterizations may be expressed mathematically as:

$$\dot{Q} = \text{MINIMUM}\,[\,\dot{Q}_{peak},\ b(t-to)^2] \qquad \text{for } t < t_{bo} \qquad (1)$$

$$\dot{Q} = \text{MINIMUM}\,[\,\dot{Q}_{peak},\ b(t-to)^2] - b(t-t_{bo})^2 \qquad \text{for } t > t_{bo} \qquad (2)$$

$$\text{where } t_{bo} = Q_{total}/\dot{Q}_{peak} + t_o \qquad (3)$$

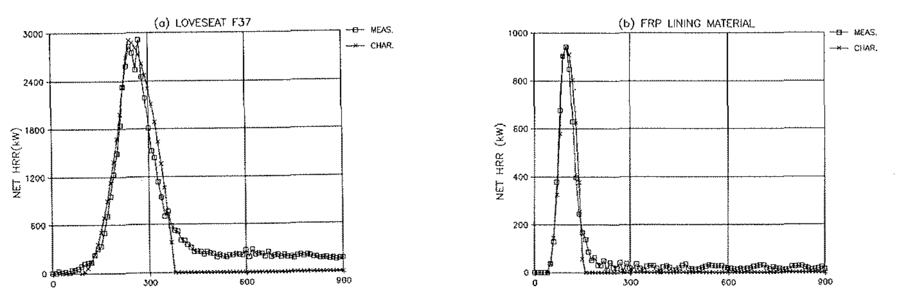


Figure 4: Measured (-x-) and characterized (-[]-) heat release rate histories for: (a) loveseat F37; (b) FRP lining material.

Such characterizations are illustrated in Fig. 4a for one of the love-seats and in Fig. 4b for one of the wall lining materials shown in Fig. 3. Four attributes are used to characterize the heat release rate histories of furnishings and finishes:

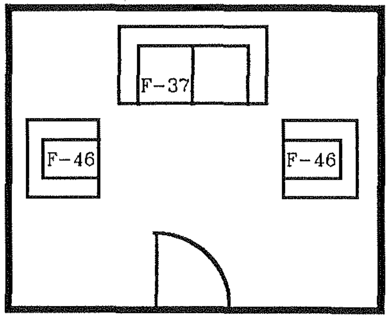
b	- the parabolic fire growth factor;
$\dot{Q}_{peak}$	- the peak heat release rate;
Q_{total}	- the total heat released by the object;
t_o	- the initial time offset or incubation time.

these characterizations have been developed to permit concise representations of actual experimental data. Thus, they apply strictly only for the experimental conditions under which the data were acquired. In the case of finishes, the characterizations are normalized in terms of unit areas. These attributes are stored in a library data base along with the other physical attributes required for the room fire analysis model.

The characterizations discussed here do not yet account for possible changes in burning rates due to radiation enhancement or other factors that might have an influence in room fires. Future characterizations of these fire attributes should be developed in terms of fundamental material properties that can be related to an appropriate fire growth model which accurately accounts for these influences. Until such a model is available, the present methodology is useful and, for the present discussion, demonstrates the concept of a library data base of physical attributes for the CAD framework.

EXAMPLE USE OF THE CAD-BASED FRAMEWORK

An example implementation of the CAD-based framework for room fire analyses is illustrated in Fig. 5, which was prepared using AutoCAD [11], the most popular microcomputer-based CAD program. This drawing is composed only of objects. A portion of the extract file for the drawing, showing the names, IDs and some of the geometric attributes of the fourteen objects comprising the drawing, is also illustrated. Once this data is extracted from the CAD system, the ID field of the extracted data is used to extract the physical attributes of the objects from the library data base, as illustrated in Fig. 1. All the geometric and physical data then is transferred to the SuperCalc4 room fire analysis model template. The user selects which object is considered to be burning, then the expected fire conditions resulting from the burning of this object are calculated as a function of time. In its current implementation, the room fire analysis model does not predict ignition of second and multiple items or the resulting combined burning rates of multiple objects.



NAME	ID	X-COORD	Y-COORD	ROTATION	X-SCALE	Y-SCALE
FLOOR	B-CONC	3.5	2.5	0.0	5.0	4.0
CEILING	B-GWB	3.5	2.5	0.0	5.0	4.0
WALL	B-GWB	3.5	6.5	0.0	5.0	1.0
WALL	B-GWB	8.5	6.5	4.7	4.0	1.0
WALL	B-GWB	8.5	2.5	3.1	5.0	1.0
WALL	B-GWB	3.5	2.5	1.6	4.0	1.0
DOOR	D-1	5.5	2.5	0.0	1.0	1.0
LOVESEAT	F-37	6.0	5.7	0.0	1.0	1.0
CHAIR	F-46	7.6	4.6	4.7	1.0	1.0
CHAIR	F-46	4.4	4.6	1.6	1.0	1.0

Figure 5: A CAD-based drawing and partial extract file.

Calculated layer temperature histories are illustrated in Fig. 6a for the two loveseats whose heat release histories are illustrated in Fig. 3a. This figure suggests that loveseat F37 burning by itself would be likely to result in full room involvement for this example, while loveseat F54 would not. Other parameters, such as total and interior heat release rates, also may be calculated and illustrated. The effect of the variation of a single parameter, such as door opening width, also may be estimated and illustrated, as shown in Fig. 6b, to analyze the influence of such

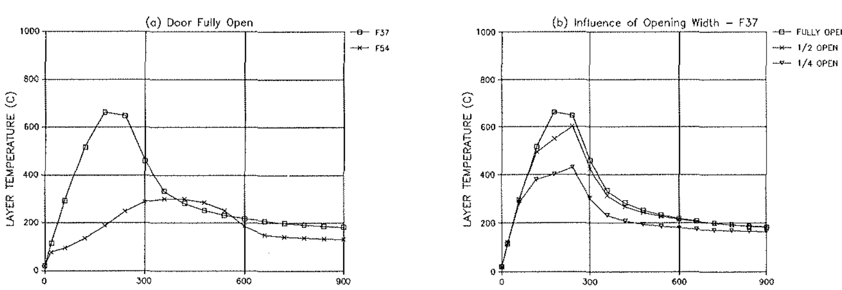


Figure 6: (a) Calculated layer temperature histories for loveseats F37 and F54; (b) Calculated effect of door opening width on layer temperature for loveseat F37.

variations on the expected conditions resulting from the burning of a single object. As with other simulation models, results of the room fire analysis model are predictive rather than prescriptive; the user ultimately must interpret results and decide upon appropriate actions [2].

SUMMARY AND LIMITATIONS

The CAD framework described here has many potential applications. It might be of use to some for the documentation within a CAD framework of objects in buildings strictly for fire safety evaluation purposes. For example, nuclear power plant operators in the United States are required to maintain extensive records of transient and fixed fuel loads in their facilities; the framework described here would be appropriate for this activity. Others might choose to incorporate fire analyses within a broader CAD-based building design and documentation framework that includes other engineering analyses. CAD is being used increasingly for facilities management, which typically includes the inventory of objects in buildings. The present framework could be set up and used in conjunction with such a system.

The spreadsheet-based room fire analysis model developed as part of this work may be a useful analytical tool to aid fire safety professionals in the evaluation of building fire safety. It can be used independently of the CAD framework. This model permits some room fire conditions of interest for fire hazard analyses to be calculated and illustrated. The primary technical value of the model as it is implemented at present is to permit determination of whether a single item burning in a room is likely to result in flashover. For the present discussion, the room fire analysis model permits identification of the objects and their attributes necessary for implementation of a CAD framework for room fire modeling.

A CAD-based framework for room fire analyses offers many potential advantages to the user. It permits drawing to be used as the primary method of recording design information and eliminates the need to re-enter data for use of an analysis model. A CAD framework also eliminates the need for people performing analyses to have at their disposal obscure physical properties data for each object. This information is stored in a library data base and is accessed by simply identifying each object. Once a drawing is developed in a CAD system, changes to the drawing may be made conveniently and fire safety consequences of these changes evaluated readily.

While the potential benefits of CAD-based building representation as a fire safety design tool are considerable, this discussion will close with an emphasis on some of the limitations of this, and perhaps all, room fire models at present. Some of these limitations include:

1. The lack of treatment of multiple item ignition;
2. A far from complete data base of fire attributes;
3. An inadequate description of entrainment rates;
4. An incomplete description of flame spread;
5. Lack of knowledge regarding severely ventilation-restricted burning rates;
6. The need for more validation;
7. Uncertainty regarding the contents of rooms at all times.

In view of these limitations, room fire analyses must be considered at present in terms of their utility to augment, rather than to replace, many traditional fire protection techniques. Nonetheless, such analyses do provide an additional quantitative tool to aid in the development of rational fire safety design decisions.

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