Geometric Modeling in the Simulation of Fire/Smoke Spread in Buildings

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Since the performance simulation of buildings, such as fire/smoke spread, energy loss/gain, acoustics, etc. greatly rely on building geometry, the way the physical environment is modeled can substantially effect the reliability of the predictions made by such simulations. Most computer models that simulate fire and smoke spread in buildings limit the computer representation of the building to simpler geometries and define rooms as rectangular spaces or as spaces with uniform crossections. Such a definition does not account for the variety of building elements that can exist in a building such as large overhangs, half height walls, etc. Existing simulations are typically developed as mathematical models and use the principles of thermodynamics to represent the spread of the elements of fire through space over a given time period. For example, in zone models each room is defined as a two tier space with heat and smoke exchange between lower and upper tiers as the fire progresses. On the other hand, field models divide the space into small contiguous units where thermodynamic state of each unit is calculated as the simulated fire progresses.

Dynamic processes such as fire and smoke spread must recognize both intangible (i.e. voids) and tangible (i.e. solids such as walls, balconies, ceiling, etc.) architectural entities. This paper explores the potential of solid modeling techniques in generating geometric definitions for both solid and void architectural entities that can interact with mathematical models of fire/smoke spread in buildings. The implications of cellular spatial partitioning techniques for zone or field models of fire/smoke spread are investigated, and the methods of creating cellular decomposition models for architectural spaces as well as for spatial boundaries such as walls are explored. The size of each cellular partition, i.e. the resolution of the partition, and the material and heat transfer attributes of each cell were found to be very critical in modeling the spread fire through voids as well as through solids in a building.

Introduction

Three dimensional geometric modeling of buildings is not only important in the visual representation of architectural environments, but also in defining such environments when the performance of buildings are simulated under different dynamic conditions such as fire/smoke spread, energy loss/gain, acoustics (Turner, 1990) etc. Since these processes are spatially constrained, the way the physical environment is modeled can greatly affect the reliability of the predictions made by such simulations.

Furthermore simulations with temporal parameters typically model the *progress of an event in a given time period through space,* thus require that the simulated event traverse a given space. This makes spatial/geometric modeling a very important parameter in such simulations. Among the performance simulations which are based on a CAD data base or a geometric modeler are the acoustical simulation program developed by J.Turner (1990), egress behavior simulation modeled by F.Ozel (1987), KB-CAAD system for the design of solar and low energy buildings (Shaviv & Peleg, 1991), interface to CAEADS from BLAST (energy simulation) (Turner, Johnson, 1985) etc.

Most computerized performance simulations originate from the discipline of physics and typically do not access a graphic data base. Currently there is an increased interest in interfacing such simulations with geometric modelers. For example, work done at ASHRAE is now directed more towards graphic data bases.

In the past, in fire spread simulations, buildings have been represented abstractly either in the form of nodes and links (network models) or in terms of grid points representing occupiable locations in a building (Stahl, 1979).

On the other hand, most existing models cannot predict smoke spread in more than a few neighboring spaces, and simplifications in modeling the geometry of spaces hinder the use of such simulations for more complex rooms such as those with balconies, half height walls etc. Typically in these simulations, spaces are abstracted as two rectilinear layers of space with a thermodynamic exchange between them. Some of the geometric attributes, such as the plan area or the total surface area of a room are built into the mathematical formulae (i.e. mathematical models of thermodynamics), and assumptions about the geometry of the building can only be inferred by studying the relationships between the variables in these formulae.

Therefore, there is a clear need to study the principles used in fire/smoke spread simulations, and to explore their geometric modeling requirements.

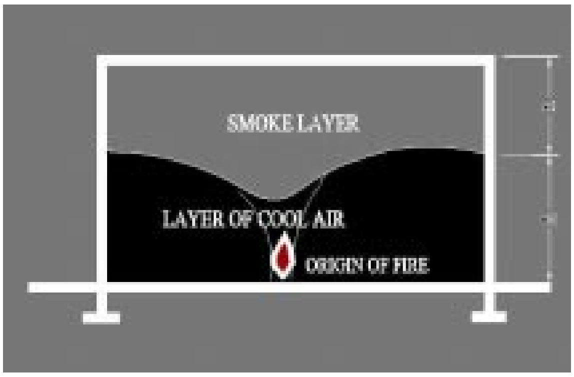

Fig. 1 Zone Models

Fire/Smoke Spread Computer Models

Typically, existing fire/smoke spread models are deterministic models that aim to simulate the conditions in a compartment fire by using mathematical models that originate from the study of the physics and chemistry of fires.

Computer models currently developed provide reasonable estimates of selected fire conditions (National Fire Protection Handbook, 17th ed.). There are two major types of computer fire models:

a. Zone models

b. Field models

The main characteristic of zone models is that they solve thermodynamics equations by treating the room enclosures as two distinct zones: a hot upper layer (d1) and a cooler lower layer (d2).(Fig1)

1). Zone models estimate the key conditions for each of these zones as a function of time .

On the other hand field models solve equations of mass and energy at each element in a compartment *space* which is divided into a three dimensional grid (Fig.2). The space in an enclosure is subdivided into imaginary tiny cubes and the physical conditions in each cube are calculated as a function of time. This model can estimate the conditions at any point in a room. Field models usually require much more computational power than zone models, therefore are not as widely used as the latter.

Some examples of zone models are ASET (Available Safe Egress Time) Cooper, et. al., 1985), CCFM (Consolidated Compartment Fire Model) (Cooper, et. al., 1990), FAST (Fire and Smoke Transport) (Jones & Peacock, 1989) and OSU (Ohio State University) model (NFPA Handbook, 17th ed., pp.10-86-91).

These simulations not only require the description of the physical characteristics of objects that contribute to the spread of fire but also the geometric description of the room(s) within which the fire is modeled. For example FAST (Jones, 1985) requires geometrical data describing the rooms and connections, and it can accommodate 10 rooms and multiple openings between them and to the outside. ASET (Cooper, 1985) requires the room floor area and room ceiling height along with the properties and the location of the fuel.

Such room information can readily be extracted from a 2-dimensional Computer Aided Design (CAD) data base. In zone models, the decision to subdivide enclosures into two layers of space and to use surface area parameters rather than volumetric parameters implies that these spaces are assumed to have uniform crossections, i.e. fires in rooms with stepped or inclined ceilings or in rooms with elements protruding into the space cannot be modeled.

Interfacing such simulations with geometric 3-dimensional modelers can provide the framework for solving the problem of simulating fires in rooms with non-uniform sections.

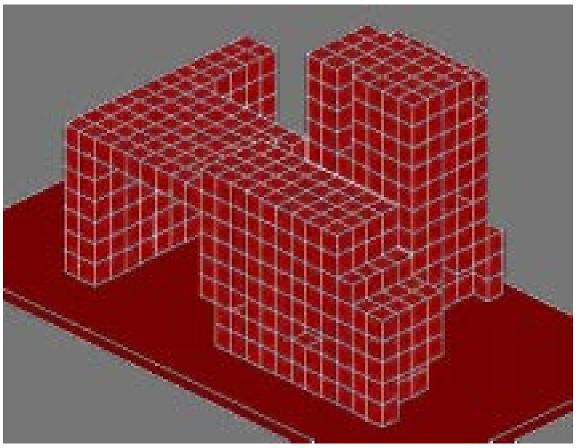

Fig.2 Field model for a single room with multiple ceiling heights

On the other hand, because field models rely on spatial elements that fill up the space (void) in a room, they have the potential to interface with 3-dimensional geometric modelers more easily. Rooms with non-rectilinear crossections, uneven ceiling heights, and/or protrusions into a space can be accounted for in field computer simulations of fires, if the building geometry is accurately defined.

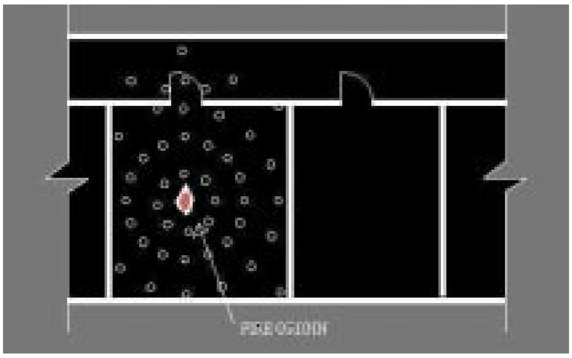

Fig. 3 Smoke spread in BGRAF

A third group of computer simulations in fire safety is behavioral models, where human response to fire is investigated. Typically in these simulations the spread of fire is modeled more simply, since the focus of the simulation is human behavior rather than the physics of the fire spread. For example, in BGRAF emergency egress model, smoke spread is simulated as a multiple pin point spread (Fig. 3) and additional remote spread is scheduled by the user. On the other hand in BGRAF, human spatial behavior and smoke spread routines are based on a Computer Aided Design data base, and are calculated by using a polygonal representation of rooms.

3- Dimensional modeling techniques

Currently, two major geometric modeling techniques are used in representing objects in 3-dimensions: surface modeling and solid modeling. Surface modeling is where objects are represented by means of a set of interconnected planar surfaces defined by bounding polygons. Because surface modeling tools do not readily define surface-void relationships, surfaces can only be used to define tangible architectural objects and their relationship to the space they enclose must be explicitly defined by the programmer.

On the other hand, in solid modeling objects are represented by volumes and the volumetric nature rather than the bounding surface of the object is stressed. Processes such as creating a section through a solid object, subtracting a void from a solid, finding the intersection of two solids (boolean operations) are only available in solid modeling. Both zone and field models must deal with the spread of fire/smoke in space which emphasizes the volumetric nature of enclosures. This makes solid modeling a better candidate as a geometric modeler for both types of simulations.

The Role of Building Geometry

In those cases, where the building geometry is implied through the use of variables in mathematical models, it may be necessary to extract the necessary input data by re-interpreting a given room geometry. For example, in zone models plan area is a parameter that is built into the mathematical models of fire spread.

Unfortunately, a single value for plan area is not necessarily the best descriptor for the varying plan-footprints that can exist at different heights of an object such as a pyramidal structure (Fig.4). To simulate fire/smoke spread realistically in such enclosures, either the formulae must be modified or the geometric modeler must continuously recalculate and update the area of the varying plan-footprint during run-time by using the current state of the simulated fire/smoke spread.

Furthermore, although it is a single space, the pyramidal structure seen in Figure 4 is complicated by the existence of multiple overhangs. Clearly the behavior of smoke generated as a result of a fire at position A will be quite different than the behavior of a fire when the origin is at B. In the latter case, depending on the size of the overhangs, there might be considerable smoke accumulation under the overhangs before smoke can start to escape towards the top of the space, whereas in the former one it will directly rise to the top. Thus the interface must create a geometric model that incorporates not only the non-rectilinear nature of a space but also a variety of architectural elements that can affect smoke spread.

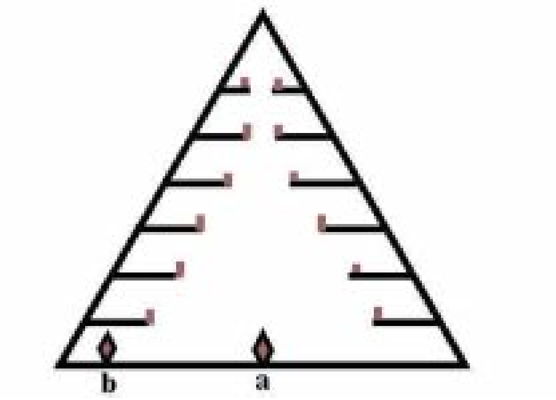

Figure 4. Pyramidal space

The formula used by zone models in calculating the filling of an enclosed space by smoke is a good example of the built-in assumptions about the geometry of an enclosure (NFPA Handbook, p. 10-105) :

$$U = m / r * A$$

where, U = rate of layer descent (m/sec)
m = mass rate of smoke production (kg/sec)
r = density of smoke layer (kg/m^3)
A = enclosure floor area (m^2)

> "*The rate at which a smoke filled layer descends toward the floor depends on the plan area of the enclosure, the distance of the lower edge of the smoke-layer above the fire, and the temperature of the layer.*" (NFPA Handbook, 17th ed. p. 10-105)

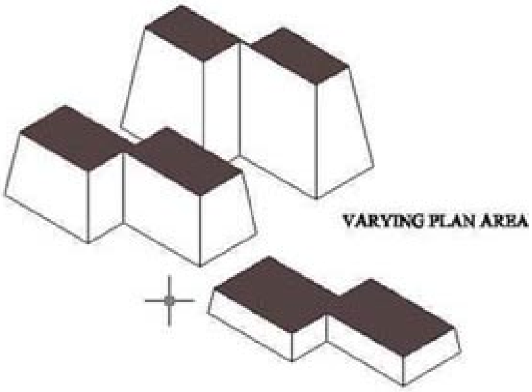

Fig. 5. Varying smoke area

This formula, as it is, will clearly underestimate the speed with which an enclosure with a slanted ceiling or pitched roof is filled with smoke. Since the calculation assumes that the plan area does not change throughout the enclosure, i.e. a rectangular crossection, the narrowing of the plan area as one goes up in such an enclosure is not accounted for.

The value of plan area "A" must be continuously modified to reflect the plan area at the lower level of the smoke layer (Fig. 5). Such a modification will require an accurate geometric model of the enclosure.

Acquiring the crossection of an enclosure at different locations at run time can best be achieved through a solid model of the void. Therefore, while at first, solid modeling techniques seem to be more appropriate only for field models (unit volume concept), a closer inspection of the mathematical basis of zone models indicates that solid modeling is also a good choice for zone models.

Spatial Partitioning

Whenever a spatially constrained dynamic process is simulated, spatial increments must be defined in order to describe the *progress of the event in a given time period through space*.

Spatial partitioning refers to the process of generating spatial increments (unit volumes) for a given space. In this kind of representation, solids are decomposed into a collection of adjoining, non-intersecting solids that are more primitive than, but not necessarily the same type as, the original solid. Although primitives may vary in size, shape and parametrization, similar to a set of child's blocks, there is a special case of spatial partitioning that is found to be very useful for spatial analysis purposes.

Spatial occupancy enumeration is a special case of cell decomposition where a given solid is decomposed into identical cells (primitives) that are arranged in a fixed, regular grid. These cells are usually called voxels (volume elements) as an analogy to pixels. The most common cell type is a cube (Fig.6).

The representation of space as a regular 3-d matrix of cubes if often called a "cuberille". In such a cuberille, only the presence or absence of a cube in a given 3-d grid point is represented in the data structure. Therefore, a complex solid object can be represented in an unambiguous way as a list of occupied cells.

One can easily determine if a cell is inside or outside a solid, or if two given solids are adjacent. This technique is widely used in biomedical technology, such as for CAT scan (Foley et.al., 1992). In general there are two major decisions to be made when a cellular spatial partitioning is done:

1. How fine a resolution to use in partitioning a solid, which will largely depend on the processing power of the computer used and the nature of the application for which the partitioning will be used,

2. How to initially represent the original solid before the partitioning is done. Architectural environments pose an additional difficulty that rarely exists in the solid modeling of other objects. Voids in an architectural environment are as important if not more important than the solids.

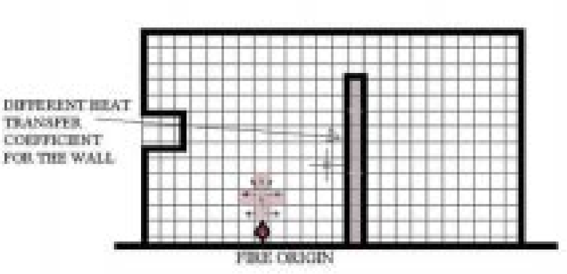

Figure 6. Cellular decomposition

Furthermore, the processing of the great number of objects that create a void, such as a room or a duct, can be a formidable task. Therefore, when cellular spatial partitioning techniques are used to represent rooms in a building, the input process must be controlled by the software designer to a great degree. In order to use such spatial enumeration techniques in generating graphic interfaces for fire and smoke spread models, there is a need to partition every void in a building into cells which can then be used by fire and smoke spread simulations.

Application of cellular spatial partitioning to zone and field models

Cellular decomposition is actually inherent in the nature of field models in simulating fire and smoke spread in a building. Through a graphic interface, the user needs to input exactly which cell contains the fire origin.

The resolution of the decomposition of the void (solid minus solid, i.e. a room) does not have to match the resolution required for a field model. The cellular decomposition of a room can typically be more coarse, i.e. it is made out of larger cubes (room-cells), whereas once the fire origin cube is determined, a second level of resolution can be introduced during the processing of the field model (Fig. 6).

Each room-cell can be further divided into a finer 3-dimensional grid for the processing of thermodynamics equations in a field model. The fineness of this second level of grid will be determined by the processing power of the computer and the level of accuracy desired in modeling the fire and smoke spread in a structure. Such a hierarchy will reduce the storage space required to represent the cellular decomposition of the voids in a building.

An additional issue in field or zone models is the conduction of heat through solids in a building. This requires the representation of not only voids (rooms, ducts etc.) but also solid components. While, a separate set of voxels can be calculated for the solids in a building, a single set of voxels with change in material and heat transfer attributes for each spatial increment (cube) that corresponds to a solid component can also be used to identify the solid boundaries of an enclosure. In the latter method, adjacency of voxels can be more readily determined (i.e. additional spatial analysis is not required to determine adjacency), but will require more processing to check the attributes of each cube each time fire spread is calculated.

An additional reason for the spatial partitioning of the solids and voids into voxels and the derivation of their adjacency information is the need to determine in exactly which room-cells the heat transfer will start in an adjoining enclosure (void).

Summary

Existing computer simulations of fire and smoke spread were studied to explore the geometric modeling needs of these models. Because of the spatial nature of enclosures and the incremental nature of the fire/smoke spread process, solid modeling techniques were found to be a better candidate for a geometric modeling interface.

Since field models are already based on a system of cellular decomposition which is implied by the mathematical models they use, geometric spatial partitioning concepts were found to be important in designing an interface.

On the other hand, input data required by the mathematical formulae which are the basis for zone models also implied a need for a solid modeling interface. At this point, further study of mathematical models are needed to determine additional geometric modeling needs before an attempt can be made to implement an interface for either type of fire/smoke spread simulations. This can eventually lead to more intuitive applications where virtual reality techniques are used.

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