Physically Based Modeling and Multi-Physical Simulation System for Wood Structure Fire Performance[1]

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Summary

This research is devoted to promoting the performance-based engineering in wood structure fire. It looks into the characteristic of the material, structural composing and collapse detecting to find out the main factors in the wood structure collapse in fire. The aim of the research is to provide an automatic simulation platform for the complicated circulation. A physically based model for slim member for beams and columns and a frame of multi-physical simulation are provided to implement the system. The physically based model contains material model, structural mechanics model, material mechanics model, as well as geometry model for the compositive simulation. The multi-physical simulation is built on the model and has the capacity to carry out a simulation combining structural, fire (thermal, CFD) and material degradation simulation. The structural and fire simulation rely on two sophisticated software respectively, ANSYS (an FEA software) and FDS (with a core of CFD). Researchers of the paper develop system by themselves to combine the two existing ones. The system has the capability to calculate the wood char to find out the loss of cross-section and to detect the collapse caused in different ways. The paper gives a sample of Chinese traditional house to show how this simulation system works.

1. Introduction

Traditional building fire research is limited. Firstly, the traditional fire codes rely on prescriptive methods to assess the fire resistance of structural components. The methods are under the standard International Standardization for Organization (ISO 1992) fire, where temperature and heat flux are fixed and all the structural components in the compartment are assumed to be uniformly heated. Secondly, the structure performance is analyzed in a manner of isolated components. In fact, the different parts of the structure are heated at different rates in real fire, the intact part of the structure may support the fire-weakened components or restraint them from thermal expansion. So, it is better to be considered as a complete entity. Thirdly, fire and structure are not considered to be interactional ones and it is difficult to analyze the coupled process, such as the structural collapse which would greatly influence the fire development. (Richard 2002)

This paper presents a new method to learn the building fire in an advanced way to overcome the limitations mentioned above. The aim of the research is to provide an automatic simulation platform for the complicated circulation. And the kernel of the platform is the physically based model and the theory of the multi-physical simulation. The physically based model contains material model, structural mechanics and material mechanics model for member, as well as

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geometry model for simulation and software integration. The multi-physical simulation is built on the model and has the capacity to carry out a simulation combining structural, fire (thermal, CFD) and material simulation. The structural and fire simulation depends on two sophisticated software respectively, ANSYS, which is an FEA software and FDS, which is Fire Dynamics Simulator, a computational fluid dynamics (CFD) fire model developed by NIST (National Institute of Standards and Technology) to predict the thermal condition resulting from a building fire(Kevin 2002).

We develop a system to combine the two existing ones, which has the capability to calculate the wood char to find out the loss of cross-section and to detect the collapse caused in different ways. And with the help of this system, fire and structure simulations can be combined into a united one and it is possible that accurate and realistic modeling of open fire can be simulated to capture the overall response of a large structure in fire.

The system has been applied in a simulation of Chinese traditional house collapse in fire. The house is made of wood and is unique in structural composing. (王天 1992)

The paper describes the main factors that influence wood structural performance in fire such as material performance characteristics of wood in fire, structure composing and structural analysis for single member and collapse. Details are described in part 2. Part 3 is about the design of slim member object model: a physically based object oriented model for slim member. The multi-physical simulation theory and system design is in part 4. Part 5 is a sample and Part 6 is conclusion.

2. Characteristic of wood building fire

2.1. Wood Pyrolysis Behavior

Fire influences the wood load carrying capacity mainly in two ways. In a lower temperature, moisture in wood will be vaporized by heating, which will change mechanical properties of wood and lower the capacity in a small range relatively(Young 2001). Exposed to a higher temperature, such as above 200°C, wood will decompose into a char layer that has no load carrying capacity. Furthermore, experiment data shows the temperature 6 mm inward from the base of the char layer is about 180°C because of the low thermal conductivity of wood, with an assumption that the temperature at the innermost zone of the char layer is 300°C. The result means the remaining uncharred cross-sectional area of a large wood member remains at a low temperature and can continue to carry a load. Thus, the amount of charring of the cross section is the major factor in the fire endurance of structural wood members.

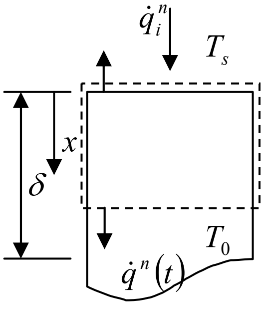


Fig.1 integral model for char depth calculation

The degradation process and the exact products of thermal degradation depend upon the rate of heating as well as the temperatures.(White 1999) Spearpoint used the integral model solutions to predict the char depth, demonstrated in Fig.1(Spearpoint 1999). Char depth can be determined by

$$\delta_{\phi} = \frac{\dot{m}^{n}}{\rho_{w}(1-\phi)}t \tag{1}$$

where ρ_w is wood density, $\dot{m}$ is burning rate, ϕ is char fraction and can be obtained by

$$\phi = 0.74\left(\frac{1}{\beta}\right)^{-0.64} \tag{2}$$

where the parameter β characterizes the magnitude of radiation and convective losses relative to the incident heat flux. It can be defined as

$$\beta \equiv \frac{\sigma\left(T_s^4 - T_0^4\right) + h_c\left(T_s - T_0\right)}{\dot{q}_i''} \tag{3}$$

where T_0 is the temperature inside the wood, which is close to the original temperature before heated; T_s is the temperature on the surface being heated. And, magnitude of radiation and convective losses can be regard as the difference by the incident heat flux $\dot{q}_i^n$ and heat flux absorbed by the surface $\dot{q}^n(t)$, shown as:

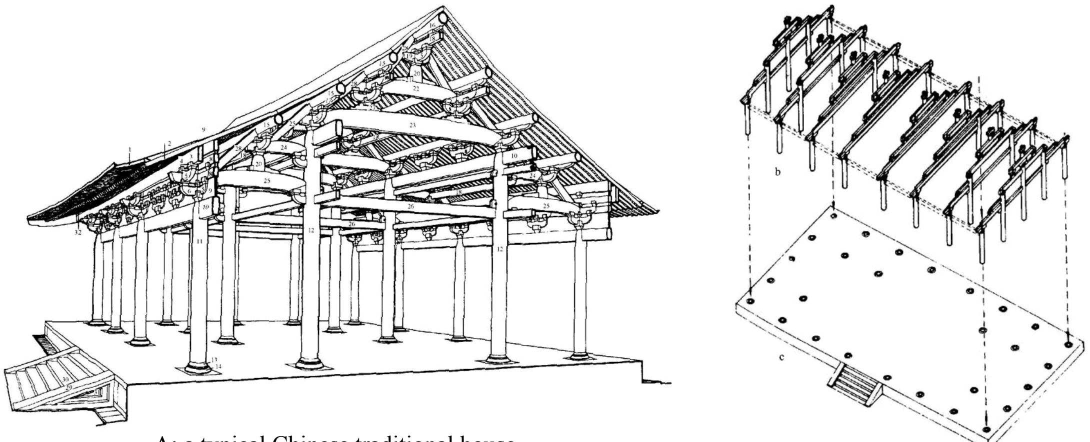
$$\sigma\left(T_s^4 - T_0^4\right) - h_c\left(T_s - T_0\right) = \dot{q}_i^n - \dot{q}^n(t) \tag{4}$$

According to the model from Spearpoint, char depth is a function of burning rate, wood density, temperature, total heat flux reached the surface and heat flux absorbed by the surface. We obtain the variables from FDS output data with BNDF (BouNDary File) namelist group by keyword BURNING_RATE, HEAT_FLUX, GAUGE_HEAT_FLUX, WALL_TEMPERATURE respectively.

2.2. Structure composing

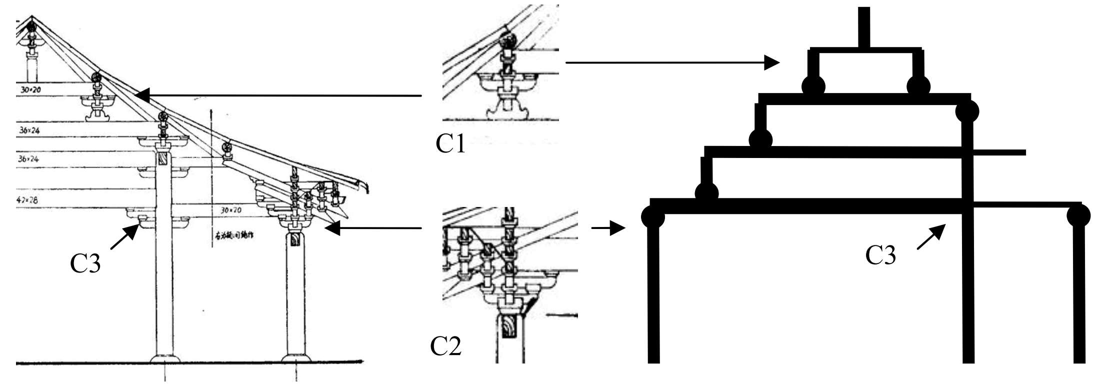
Chinese traditional wood house is unique in structure composing. A typical one is shown in Fig.2A, which is composed by foundation, framework and roof. Fig.2B shows that the framework is constructed by several pieces of planar frame. Different pieces of frame are linked by roof beams with hinge joint, which also bear the weight of roof. Fig.2C shows the structure of a single planar frame, which is assembled with three kinds of typical connect. The first one is marked with C1. It is used to support a beam from a lower beam. The support is a short pillar with an expanded end at the upper end. The upper end is strong in constraining the rotation of the upper beam, so it is regarded as a rigid connection. The lower end is relatively weak and is modeled as a hinge joint. The second kind is marked as C2, which is similar to C1. It is used as connection between column and beam as a hinge joint. The third is a rigid connection, marked with C3 in the figure. In the C3 connection, beam and column intersect with each other to act as a united one.

Fig.2D shows the abstract structural model of the Chinese traditional house with various kinds of connection. The bold ball end refers to a hinge joint, while others for rigid connection. The size of the members can be achieved from the archaeology. In Fig.9C, a figure of structural model in ANSYS is showed.



A: a typical Chinese traditional house

B: assemblage of the structure



C: structure of a single planar frame

D: abstract structure model

Fig.2 structure composing of Chinese traditional house

2.3. Member Check

Wood is an orthotropic material; that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential, shown in Fig.3. The length direction of the slim member is ordinarily consistent with the longitudinal axis. Member checking is carried out by calculating the cross-section which is vertical to longitudinal axis.

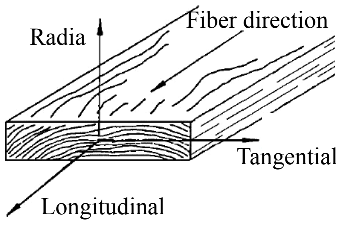


Fig.3 three principal axes of wood

There are two kinds of load in building fire: force load and fire load. The force load is common is structure analysis, which has sub-kinds of axial load, bending, combined bending and axial load and destabilizing effect. Deference yields from the orthotropic of the material. Direct stress along the longitudinal axis and shear stress are compared with compressive/tensile strength parallel to grain and shear strength vertical to grain respectively. The stress in the two direct need not be combined because of the orthotropic. The fire load is the cross section area loss caused by pyrolysis. The force load crashes the member by overloading, while fire load by reducing the bearing capability.

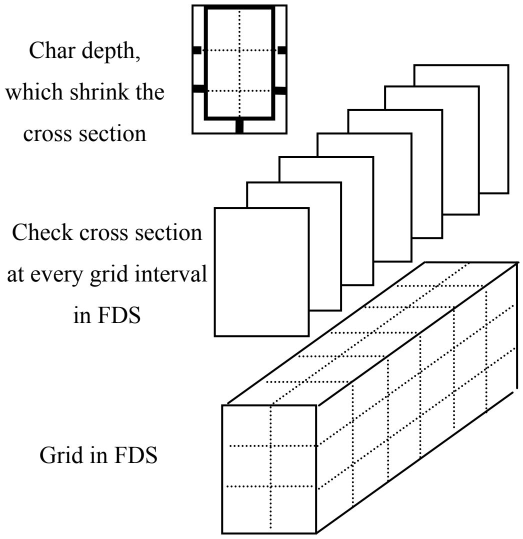


Fig.4 data format in FDS

Because of randomness of the temperature distribution along the member, it is no longer adequate to check the cross-section at two ends and the mid-span, where the maximum bending load or shear load is located. Cross section should be checked as frequently as possible, including the three above, because the fire load may crash the member at arbitrary position by reducing the cross section enough to be overloaded by the stress there. So we check the cross section at every grid interval in FDS, shown in Fig.4.

Stress and can be achieved in ANSYS calculation result. To get the load at two ends and mid-span of the member, member has been meshed into two elements. Then, stress on the cross sections at every grid interval can be calculated by linear interpolation. It suffers some error when a member bears a uniform load, such as roof beams, whose bending moment diagram is a curve, but the error is not much.

2.4. Collapse

Collapse can be defined as removing members from the structure framework. In a fire disaster the collapse is no long a single occurrence taking place at one time point, but a process of one batch after another.

The collapse recognized in a traditional structural analysis is due to the simple cause that load exceeds the bearing capability, while in disaster more causes have taken effect. In addition to bearing capability being exceeded due to the member cross-section loss caused by heat, which is regard as a direct manner, there are other two kinds of indirect ones.

The first one acts when part of the structure turns into a mechanism after several members are removed from the structure. The member involved in the mechanism is not damage directly by the cross-section weakening but it could no long act as a structural member. What is more, the mechanism halts the ANSYS calculation for structure. So they must be marked out. The second kind of indirect damage is cause by the stress re-distribution when members are removed from the frame and the system of the structure is changed. The re-distributed stress of some members will probably exceed the bearing capability of other members which haven't been damaged before the first members are removed.

Direct damage is caused by the fire load. Indirect damage is caused by the change in structure system and may cause further step of indirect damage.

To check out the indirect damage in the simulation, we employ different methods for different kinds. For the first kind, structure will be calculated for a second time. In the second calculation, members to be removed will not be deleted directly, but modeled as a weak enough member, which has very little rigidity. It is also necessary to add a horizontal gravitation as a disturbance. The members in mechanism under the disturbance will suffer great displacement, which can be easily found out by comparing with the original ones. For the second kind, a new ANSYS calculation is invoked to gain the new stress distribution to check out whether new members are overloaded. The structure model for the new calculation contains no more directly damaged members and members in mechanism.

Fig.5 shows the complete flow chart of the collapse checking. The damage checking process begins with direct damage checking, which needs result data from FDS simulation and ANSYS calculation. If the result of direct checking shows that some members have been burned down, checking for indirect damage is invoked. The first step of that is to find the members form mechanism. The system re-models the input model for ANSY by reducing the rigidity of those members and feeds it to ANSYS simulation 2. The difference between ANSYS simulation 1 and 2 is that 1 gives out result of load on each member while 2 provides displacement of nodes as result. ANSYS simulation 2 is special for mechanism detecting. Then the members burned down directly by the first and those form mechanism are all removed from the ANSYS input model to perform a new instance of ANSYS simulation 1. The new invoking of ANSYS simulation 1 will

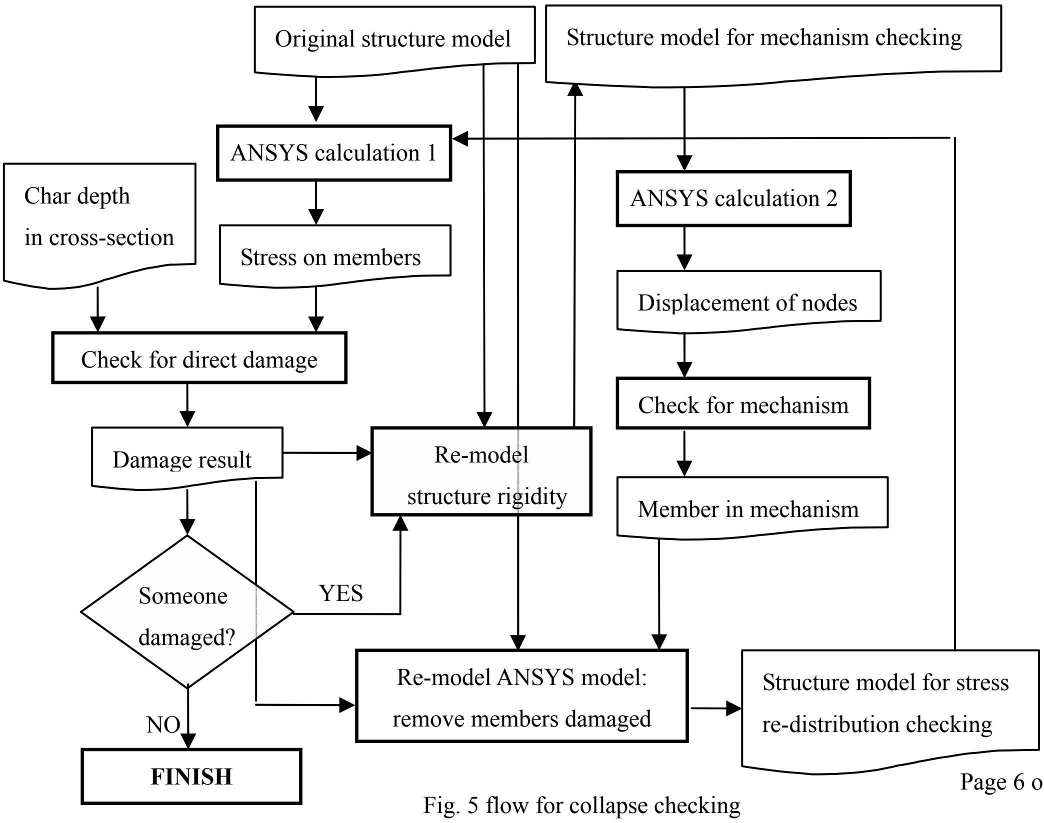


Fig. 5 flow for collapse checking

tell whether some of the members left will be damaged by the re-distributed stress. The process forms a circulation and will not stop until no damage is found out.

3. Physically Based Slim Member Object Model

The purpose of this research is to combine the fire simulation and structure analysis into an integral automatic one. Physically based model for slim members such as beams and columns is the key for the integration. As shown in Fig.6, the object is used in modeling, data reading and statement checking. The data to be modeled include geometry data, relationship of geometry

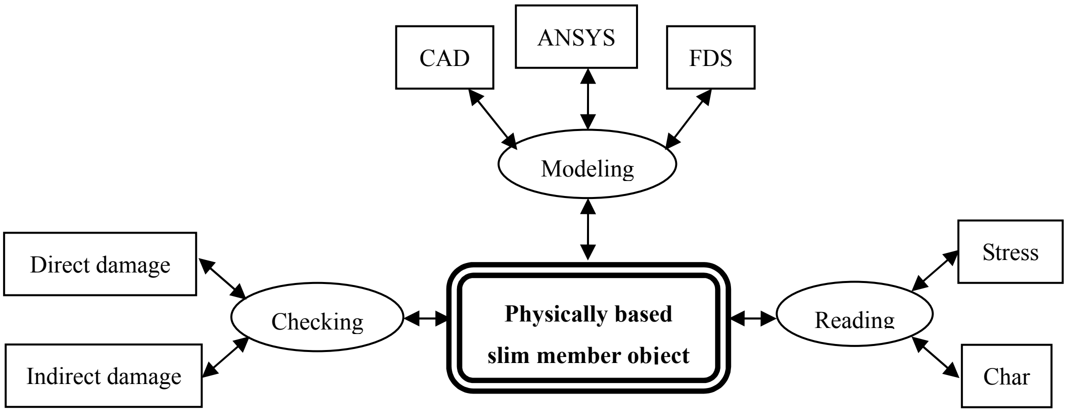


Fig.6 functions of the Physically based slim member model

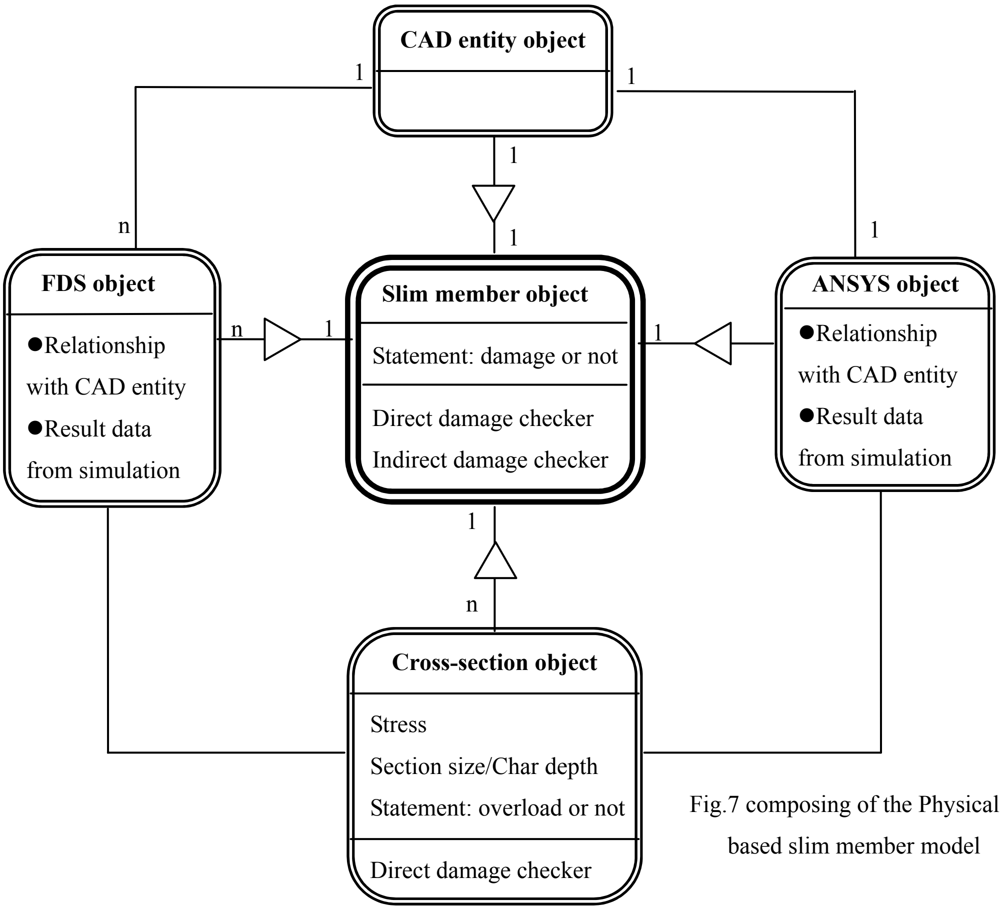


Fig.7 composing of the Physically based slim member model objects and coordinate match protocol in different subsystem, such as CAD, ANSYS and FDS shown in the figure. Data to be read are from result of FDS and ANSYS, from which member stress and char depth can be calculated. Direct damage and indirect damage can be checked out by the checking module, which contains mechanical model and material pyrolysis model.

Fig.7 shows the composing of the slim member object. The object is made up of four main sub-objects: ANSYS object, CAD entity object, FDS object and cross-section object.

ANSYS object maintains the data set from ANSYS, such as element index, element geometry, section size and loads on the ends, and the relationship with the CAD entity object. Similarly, FDS object holds the data set from FDS, such as obstruction index, obstruction geometry and char depth on the obstruction surface, and it also has the relationship with the CAD entity object. Via their relationship with CAD entity object, the relationship between an ANSYS object and an FDS object can be found out. ANSYS object and FDS object both offer a method to manipulate the APDL file (ANSYS modeling file) or data file (FDS modeling file) respectively. The file manipulating method will not only read the data from the file to perform a simulation, but also update the rigidity of the member or remove the member in APDL file or append remove time to FDS's data file when collapse takes place.

Cross-section object is corresponding with the control section shown in fig.4. The major task of the object is to check the direct damage, details of which are comparing the result from the ANSYS with those from FDS. Before the comparison, the cross-section object will reorganize the result data into a format that can be used by the direct damage checker. The crude data directly coming from the output files are char depth value list in an order of faces. They will not be available data until they are reorganized as data about the control section. The ANSYS result gives out the load on the two ends and mid-span of the member, which will be used to calculate the load on the control section.

The main object is in charge of checking out when and where the member is broken. It has failure checkers available for both indirect damage and direct damage. For direct damage, it will check out all the cross-section objects it has to find out whether some of them are overloaded and define the kind of the crash and locate the position. For indirect damage, it will check the displacement of node directly from ANSYS object. The details of the checker can be found in chapter 2.4.

4. Multi-Physical Simulation

The process of structure collapse is an interactional process combined with fire development, material degradation and structure performance. The complete flow of multi-physical simulation is shown in Fig.8.

The simulation begins with FDS simulate. For the characteristic virtue of CFD, which act as the calculation core of FDS, the simulation of FDS is carried on by time intervals. So, the result of FDS is composed by result at every time point. The structure damage checking must be carried out for every time point orderly.

When we look into a data slice of a single time point, we can find that it contains thermal data on every face of each obstruction. Because a structure member will correspond to several obstructions in FDS, it is necessary to filter out the obstructions relative to the certain member first. Then the thermal result of obstructions and the force load of the member (which can be achieved from ANSYS calculation result) will feed to a slim member object mentioned above as initial data. The slim member object has the capacity to define material degradation and execute a member checking. The detail of the damage checker in slim member object is shown in Fig.5. So, the initialized object will tell if the member is damaged. After such process being done for each member in this time point, it is clear that how many members have been burned down at that time.

If the count of member damaged at time point marked with BKPT (which refers to BreaK PoinT) is above zero, the member checking processes for subsequent time points will be interrupted. Then the system will update the FDS input model by specifying remove time with BKPT for the obstructions corresponding to the damaged member and invoke a new FDS simulation based on the new input model.

After the new FDS simulation finishes, the member checking process will continue from the BKPT to find out the structure performance from that time on. The circulation will not stop until the member checking process for the last time point is finished.

After the three circulations are worked out, the time of the member broken of the structure can be obtained entirely.

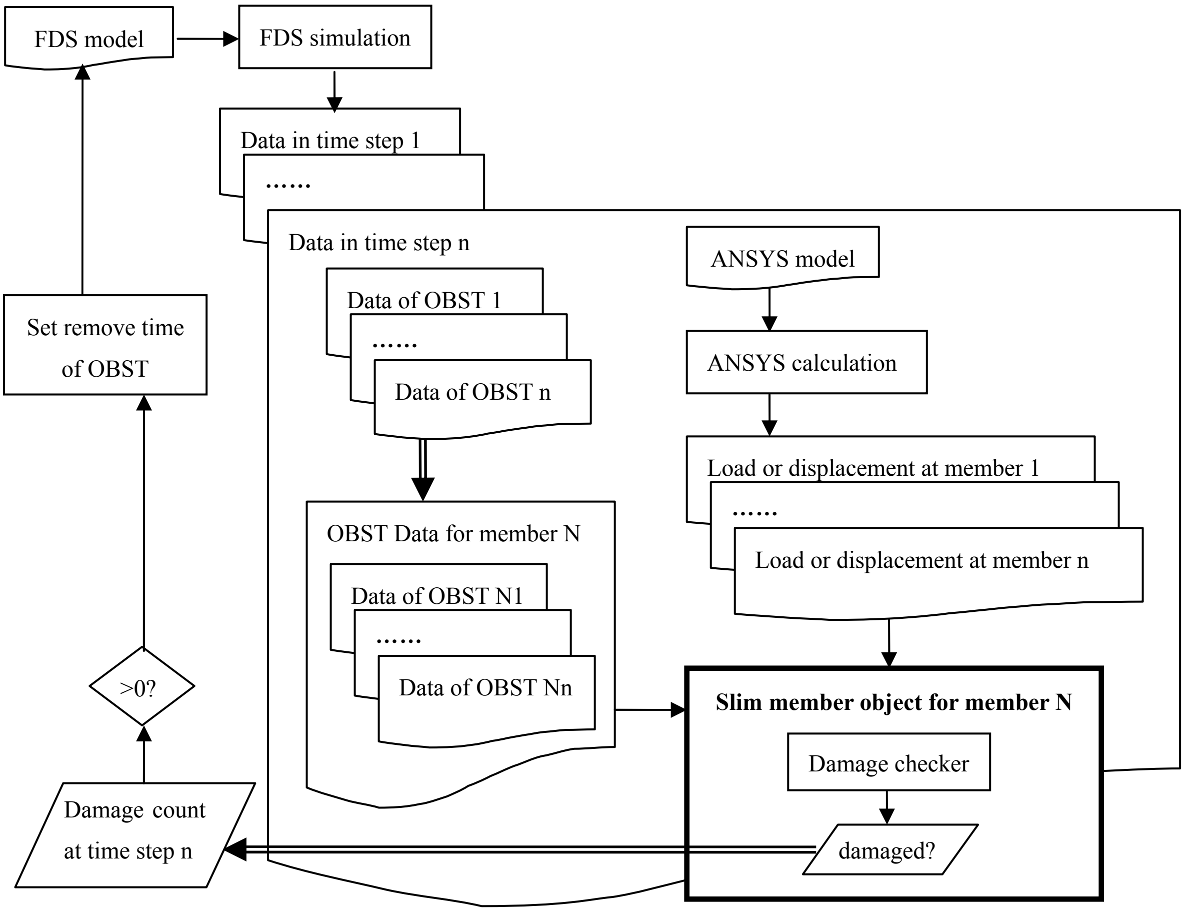
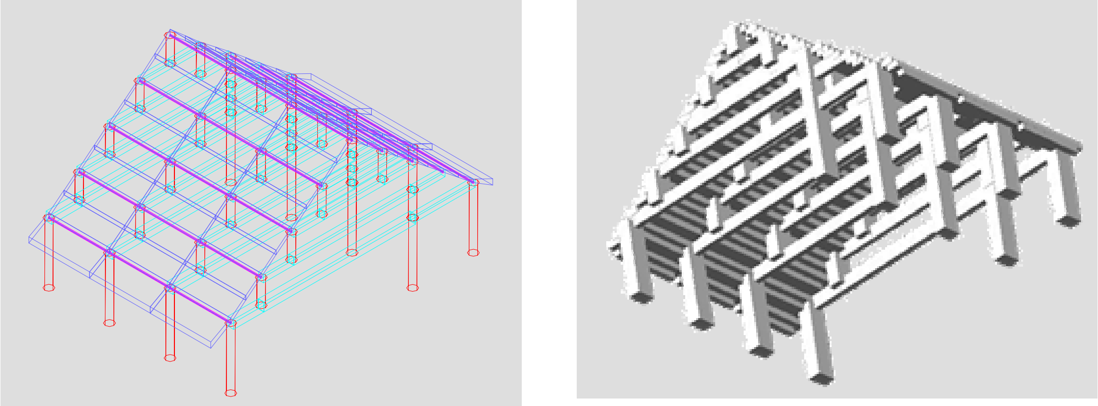


Fig. 8 flow of multi-physical simulation

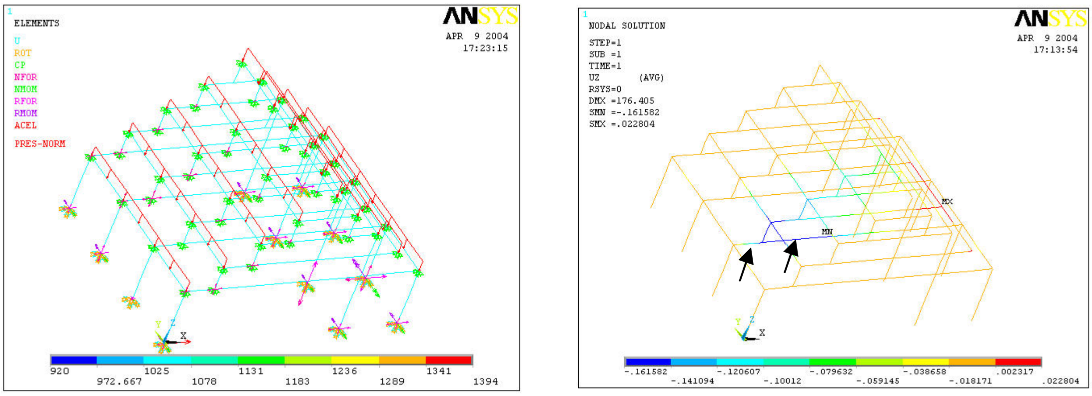
5. Implementation and Sample

A system is developed to perform the multi-physical simulation. The system is composed by a modeler and a simulation controller. The modeler is employed to translate a CAD model (as



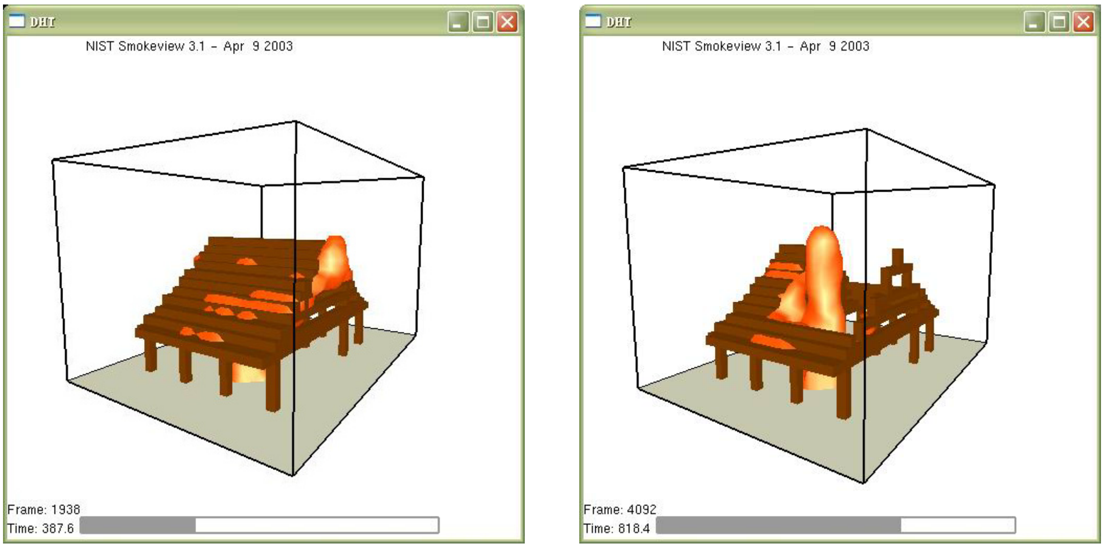
A: AutoCAD model

B: the visualization of the FDS input model translated from AutoCAD model



C: ANSYS model

D: the displacement of nodes after some member is burned down



E: fire before collapse

F: fire after collapse

Fig.9 a sample simulated by the system

shown in Fig.9A) to FDS input model (shown in Fig.9B). The modeler is very useful to overcome the shortcoming of FDS in geometry modeling. With the help of the model, arbitrary body can be modeled with arbitrary resolution for FDS. Another duty of the model is to maintain the relationship between the model in CAD, FDS and ANSYS. Fig.9C shows an ANSYS model, in which roof is substituted by uniform load. The relationship is represented as relevancy among entity handle in AutoCAD, member number in ANSYS and obstruction index in FDS. The simulation controller is built on the physically based slim member object and is due to execute the multi-physical simulation automatically.

The latter three pictures in Fig.9 show the result of the simulation. Fig.9D, as well as Fig.9C, are achieved as hard copy from ANSYS. Fig.9E and Fig.9F are two snapshots from the SmokeView. SmokeView is the visualization tool offered in company with FDS, with which the whole animation of fire can be viewed. In Fig.9F, you can clearly find that the fire source is straight under the main beam in the second piece of planar frames. Fig.9E shows the fire development before the beam is burned down while Fig.9F is about the situation after the collapse. Fig.9D shows the displacement of nodes after the beam is burned down to be used to check the indirect damage, which is pointed out with the arrows and have defferent colors.

6. Conclusion

The paper looks through the characteristics of the wood structure performance in fire, including material pyrolysis, structure composing, member failure and sequencing of collapse. The research is devoted to develop a system to simulate the complicated process of the wood structure collapse in fire, which is once simulated in isolated structure and fire simulation. The system employs two sophisticated software, ANSYS and FDS, as sub-modules to practise the structure analysis and fire simulation. The system has modules based on physical based slim member object that take into account the characteristics of the wood structure performance in fire and act as a shared data structure to combine the two isolated software. The physical based object can reorganize thermal data from FDS and mechanical data from the ANSYS, and it can deal with the char depth calculation and checking out the damage to tell when and where a member is broken. With the help of the model and system, we can accomplish the fire simulation and structure analysis in a coupled way, which is more agreeable with the performance based fire engineering. The system is applied in a Chinese traditional house. We continue to work to upgrade the model and system for new material and new structure, such as steel structure. With some promoting, it can be used widely in fire disaster reappearance and prediction, fireman training and so on.

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