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Safety monitoring system of steel truss structures in fire

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ABSTRACT

The fire-induced collapse of steel structures is very likely to cause secondary casualties in fire rescue. In order to predict the structural response, as well as give early warning of the collapse location of steel truss structures in fire to the rescue team, this paper develops a safety monitoring system for steel truss structures. Firstly, the theoretical basis of the system, including the member failure index and the collapse index is derived. Secondly, a numerical example is analyzed in SAP2000 to illustrate the calculation process of the collapse index, and the results indicate that the limit value of the collapse index can be chosen as 0.45. Subsequently, the development of the system, including the theoretical framework, the design of the system, and the user interface, is described. Finally, the system is used to monitor a fire test on a steel truss roof structure. The comparison of the output and experimental results indicated that the system is able to evaluate the real-time status of the members and the global structure. Besides, the structural response predicted by the system can be given to the user 180 s ahead of time, which provides precious information for the fire brigades to determine a safer route during the rescue process.

1. Introduction

According to the data of the World Fire Statistics Center, about 7 million fire accidents happen every year worldwide, and the number of casualties can reach up to about 70,000. Among all kinds of fire accidents, building fire accidents are the most threatening to mankind. Specifically, as steel trusses have widely been used as the roof structures of large-space enclosures, their sudden fire-induced collapses can trap people inside the building, which leads to tremendous losses of human lives and properties. Even worse, without knowing the real-time status of the structure in fire, instructors cannot give the most accurate rescue decision, resulting in secondary casualties. Therefore, a structural safety system in fire, which monitors the real-time structural behavior and predicts the collapse of the structure, is essential for mitigating the hazard caused by building fires.

As an essential prerequisite, as well as responding to the concept of the performance-based fire design [1], the global fire-induced collapse behavior of steel structures has dragged the attention of many researchers. Based on the Vulcan software developed by the University of Sheffield, Sun et al. [2,3] obtained the failure modes and corresponding internal force changes of steel frames under single column fires and multi-column fires. Fang et al. [4,5] proposed the evaluation method of the progressive collapse resistance of steel structures with composite floors under localized fire, with and without considering the temperature. Jiang et al. [6,7] studied the progressive collapse mode of planar steel frames under localized fires, and analyzed the dynamic failure mechanism of constrained columns, based on which a simplified evaluation method was proposed. With respect to steel truss roof structures, Lu et al. [8] carried out a case study of the fire behavior of the roof structure of an exhibition center, and some suggestions for enhancing the fire resistance were given. Most recently, Jiang et al. [9] conducted a full-scale fire test on a steel truss roof structure, and detailed failure mode, structural and thermal responses were exhibited, which provided experimental data for verification.

However, studies on the monitoring and early warning of fire-induced collapses are relatively rare. For the time being, the warning and prediction are mainly realized based on the deformation, vibration characteristics, and other parameters of structural components in fire. Qu and Wang [10] developed an instrument to measure the vertical displacement of reinforced-concrete frames in order to predict the global failure of the structure. Based on the structural fire resistance test data, Bai et al. [11] obtained the variation of structural parameters in fire, and found that the deformation velocity of members is the most related to the collapse of the structure. Duron et al. [12] conducted tests on the vibration of wood structures under fire conditions, and proposed that the structural damage can be evaluated by monitoring the structural vibration, so as to predict the collapse. However, traditional instruments, including vibration or displacement sensors, are very likely to be destroyed in fire, thus making their data invalid. To solve this problem, Madrzykowski and Kent [13] tried to verify the feasibility of using the

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thermal imager for temperature monitoring to realize the prediction of the integrity of structural wood plates in fire. Disappointedly, the results indicated that the data measured by the thermal imager had a large error, compared to the precise data measured by thermocouples. Therefore, a potential safety monitoring system may be based on the data produced by thermocouples.

This paper aims at developing a safety monitoring system for steel truss structures to provide the fire brigades with the real-time state of the structure. Firstly, the theoretical basis, including the component importance coefficient, the failure index of truss members, and the collapse index of the structure in fire, are introduced. Then, the numerical analysis is carried out using SAP2000 to explore the limit value of the collapse index. Subsequently, a steel truss safety monitoring system based on temperature index to evaluate the global structural behavior, and to predict the fire-induced collapse, is developed. Finally, the system is tested using the results of the fire test conducted by Jiang et al. [9].

2. Theoretical basis for safety monitoring of steel truss in fire

2.1. Member importance coefficient

Arranging sensors for all the members in the structure will lead to considerable cost. Instead, it should be more reasonable to place sensors for important members. Therefore, it is necessary to evaluate the importance of each member in the structure.

When evaluating the progressive collapse resistance, a concept called *robustness* was proposed [14], which indicates the structural capacity of resisting the global failure of the structure, under the circumstance of local damage. Scholars have proposed several models of the member importance index to quantitatively evaluate the role of the member in a structure, including models based on the structural topology [15–16], the probabilistic risk [17], and the energy method [18]. Among these models, the model based on the energy method can consider the action of load, as well as the influence of the single-member on the whole structure, rather than a local area. Hence, the importance coefficient of the members is calculated based on the strain energy:

$$\gamma_i = 1 - \frac{U}{U_i} = 1 - \frac{\mathbf{R}^{\mathrm{T}}\mathbf{K}^{-1}\mathbf{R}}{\mathbf{R}^{\mathrm{T}}(\mathbf{K}_i)^{-1}\mathbf{R}} \tag{1}$$

where γ_i is the importance coefficient of the ith member; U is the total strain energy of the perfect structure; U_i is the total strain energy when the ith member fails; $\mathbf{R}$ is the external load; K_i is the structural stiffness matrix when the ith member fails.

2.2. Failure index of truss members

The structural safety monitoring at room temperature mainly involves the frequency, deformation, and strain (stress) of the structure, and the state of the structure can be judged by their variation. However, traditional sensors are difficult to work stably in fire due to the high temperature, while the thermocouples can produce stable and reliable temperature data. Therefore, this section tries to investigate a member failure index based on the temperature.

In steel truss structures, the members can be regarded as two-force bars, which only bear axial compressive or tensile forces. Let Q and q denote the member stress ratios at elevated and room temperatures. For axial compression ($N < 0$, N is the axial force):

$$Q = \frac{N}{\alpha_{\mathrm{c,T}}\varphi\eta_{\mathrm{T}}fA} \tag{2}$$

$$q = \frac{N}{\varphi fA} \tag{3}$$

where $\alpha_{\mathrm{c,T}}$ is the influence factor of the axial-compression stability coefficient at T°C, φ is the axial-compression stability coefficient at room temperature, η_{T} is the reduction factor of the yield strength at T°C, f is the room-temperature design strength, and A is the area of the cross-section. For axial tension ($N > 0$):

$$Q = \frac{N}{\eta_{\mathrm{T}}fA} \tag{4}$$

$$q = \frac{N}{fA} \tag{5}$$

It can be seen from Eq. (2) and Eq. (4) that only $\alpha_{\mathrm{c,T}}$ and η_{T} are related to the temperature. Besides, Q equals to q at room temperature T_0, indicating the safest condition; the member fails when its temperature reaches the critical temperature T_{cr}, and the corresponding stress ratio $Q = 1$. Therefore, Q can be used to evaluate the stress state of the member, which is defined as the member failure index. In order to provide early warning of the failure, the state of the member has been divided into six different levels according to the development of Q, namely safe, secondary safe, secondary dangerous, dangerous, critical and failure, where T_{si} ($i = 1, 2, 3, 4$) is the member temperature of at the ith level. While Q varies from q to 1, the range "q ~ 1" has been classified into 5 parts to correspond to the six danger levels, as shown in Table 1.

2.3. Collapse index of truss structures in fire

When a member fails in fire, the truss structure may collapse due to the chain reaction. Hence, it is necessary to explore an index, which can identify the risk of global collapse due to member failure in order to raise an early warning.

The total structural strain energy will increase with the failure of a single member. Meanwhile, if the global collapse is triggered due to internal force redistribution, the members near the failed member will present excessive deformation, resulting in a larger increase in their strain energy. Hence, the proportion of the strain energy of the affected members to the total strain energy can be used to characterize the possibility of global collapse, which is defined as the collapse index I_{pc}:

$$I_{\mathrm{pc}} = \frac{U_{\mathrm{a},i}}{U_{\mathrm{t},i}} \tag{6}$$

where $U_{\mathrm{a},i}$ is the sum of the strain energy of affected members, when the ith member fails; $U_{\mathrm{t},i}$ represents the total structural strain energy when the ith member fails.

Considering the characteristic of truss structures, the affected members can be determined according to the follows:

(1) A chord member fails - all the members in its zone, and the two adjacent zones;
(2) A web member fails - all the web members in its zone, and the two adjacent zones.

The visual illustration of the location of the affected members is given in Fig. 1.

Table 1
Classification of member danger levels.

Failure index Q	Level	Member temperature
q	0: safe	T_0
$0.8q + 0.2$	1: secondary safe	T_{s1}
$0.6q + 0.4$	2: secondary dangerous	T_{s2}
$0.4q + 0.6$	3: dangerous	T_{s3}
$0.2q + 0.8$	4: critical	T_{s4}
1	5: failure	T_{cr}

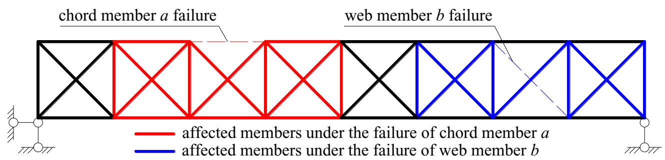


Fig. 1. Visual illustration of the location of the affected members.

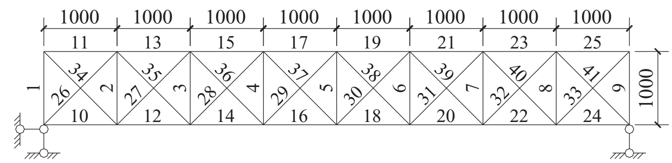


Fig. 3. Diagram of the numerical model.

2.4. Calculation procedure of the limit value of steel truss in fire

Based on the aforementioned indexes, the limit value of the collapse index can be determined according to the procedures exhibited in Fig. 2. Note that the calculation of γ_i serves as a general selection of the important members, on which sensors can be placed. Afterward, the calculation of $I_{pc,i}$ should be more precise in predicting the status of the structure.

3. Numerical example

This section aims to illustrate the determination of the limit value of the collapse index for the safety monitoring system of steel truss structures in fire by means of numerical analysis, in order to give early warning of the collapse.

3.1. Numerical model

A simple steel truss model is analyzed in SAP2000, as shown in Fig. 3. The span of the truss is 8 m, the height is 1 m, and the width of each zone is 1 m. All of the members have a cross-section of □40 × 2, and are made of Q235 steel. In order to simulate the structure in service, the dead load of the truss is $g = 0.5$ kN/m^2, and the live load is $q = 0.5$ kN/m^2. The load combination is "1.2 g + 1.4q", and the load is distributed to the joints of the top chords by assuming the longitudinal distance between adjacent trusses as 4 m.

Steel trusses are mainly used in large-space structures such as factories and shopping malls, where the fire is usually regarded as localized fire. Therefore, single members are removed to simulate the failure caused by localized fires, and the corresponding stress ratio of the structure will be calculated to check whether the structure collapses.

3.2. Numerical results

The calculation result of I_{pc} of the truss structure after removing each member is tabulated in Table 2, and the corresponding stress ratio of the structure is shown in Fig. 4. Note that the stress ratio is calculated with respect to the yield strength, which indicates that when the stress of any microelement on the section of the member exceeds the yield strength of the material, the stress ratio will exceed 1.0.

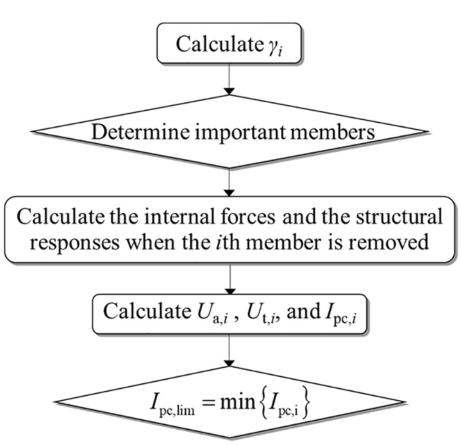


Fig. 2. Calculation procedures of collapse index limit value.

An example is given for the calculation process of the I_{pc} of member 18:

(1) Calculation of $U_{t,18}$: Calculate the strain energy of the whole structure, and $U_{t,18}$ equals to 271.34 N·m;
(2) Calculation of $U_{a,18}$: Calculate the strain energy of the affected members. According to the illustration in Fig. 1, the affected members include members 4–7, members 16–17, members 19–21, members 29–31, and members 37–39. $U_{a,18}$ is the sum of the strain energy of the members mentioned before, which equals to 210.84 N·m;
(3) Calculation of $I_{pc,18}$: According to Eq.(6), $I_{pc,18} = U_{a,18}/U_{t,18} = 210.84/271.34 = 0.777$.

It can be seen in Table 2 that the collapse index of the structure is in good agreement with the response of the actual structure. That is, the collapse index is able to describe the damage degree of the structure.

As can be seen from Fig. 4a, the stress ratio of the web members was small. Correspondingly, most of the members remained elastic after removing a web member. However, when a chord member was removed, the stress ratios of the chord members and oblique web members in its zone all increased dramatically. Besides, from the results exhibited in Fig. 4f and g, it can be seen that the stress ratios of the two-way web members both increased, while the truss did not collapse, so it can be concluded that the safety of the truss can be improved with double-diagonal web members. When the members with a stress ratio larger than 1.0 were no longer able to transmit the load, the structure became geometrically deformable and was regarded as having collapsed.

In order to explore the variation of I_{pc} with respect to the structural response, model A and model B are analyzed based on the original model in Section 3.1. The section of the lower chord of model A is reduced into □20 × 1, and the load of model B is 1.5 times of that of the original model. The calculated results are also summarized in Table 2. It can be seen that I_{pc} increased for the modified models, while the structural response of removing member No.22 changed from "all elastic" to "collapse". Therefore, there should be a limit value of I_{pc}, above which the structure collapses. For all the collapsed structures, the frequency distribution histogram of their corresponding I_{pc} is shown in Fig. 5, where results of the original model and the modified models are included. Most of the instances were distributed between 0.5 and 0.9,

Table 2
Summary of the collapse index results of the models.

Element number	Original model		Model A		Model B	
	I_{pc}	Response	I_{pc}	Response	I_{pc}	Response
6	0.007	All elastic	0.008	All elastic	0.008	All elastic
18	0.777	Collapse	0.906	Collapse	0.931	Collapse
20	0.683		0.798		0.818	
21	0.676		0.789		0.810	
22	0.441	All elastic	0.514		0.470	
24	0.196		0.229	All elastic	0.209	All elastic
30	0.008		0.009		0.008	
31	0.026		0.032		0.028	
32	0.076		0.089		0.081	
33	0.075		0.087		0.080	

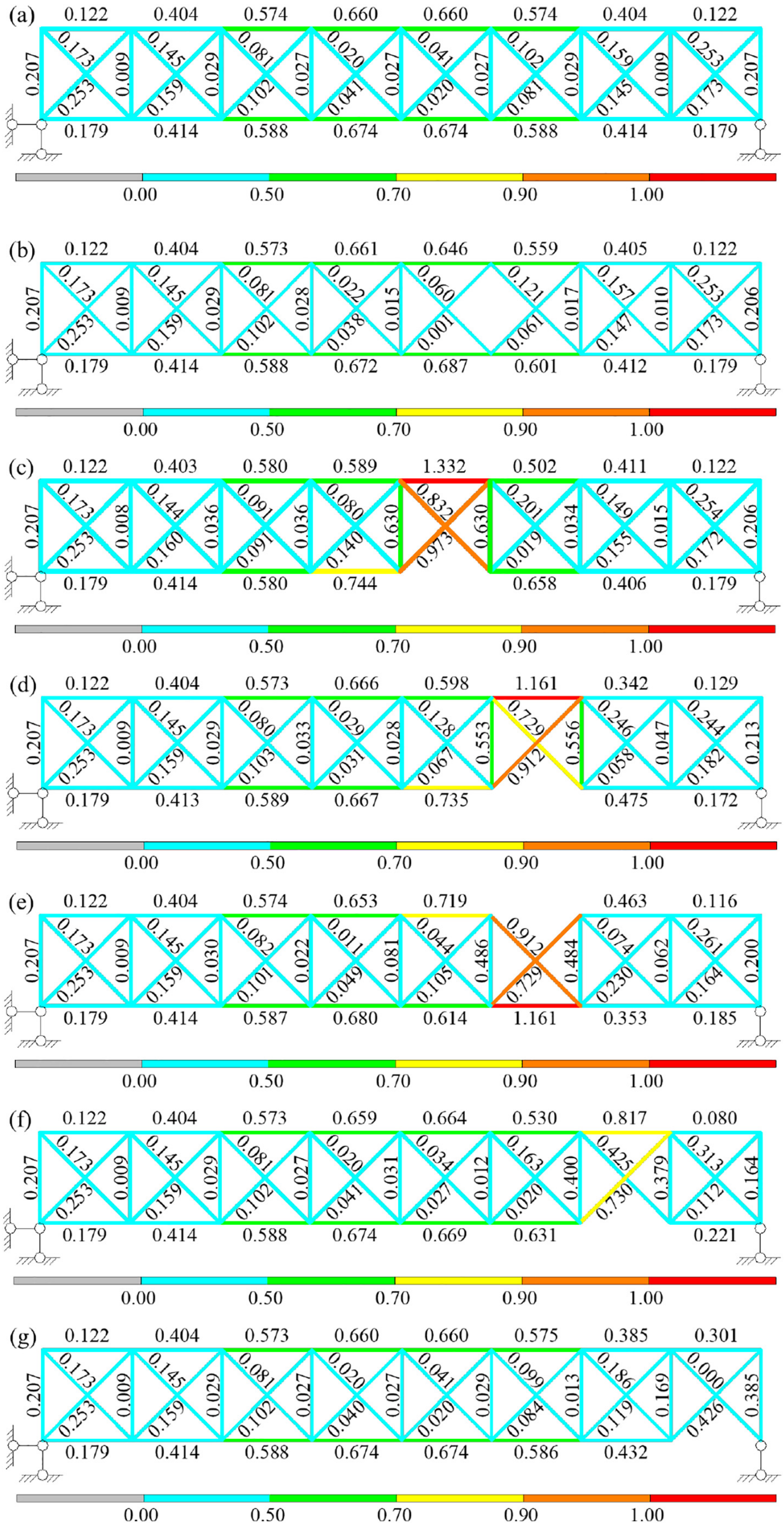


Fig. 4. The stress ratio of the structure after the demolition of some components. (a) Original structure. (b) No. 6. (c) No. 18. (d) No. 20. (e) No. 21. (f) No. 22. (g) No. 24. (h) No. 30. (i) No. 31. (j) No. 32. (k) No. 33.

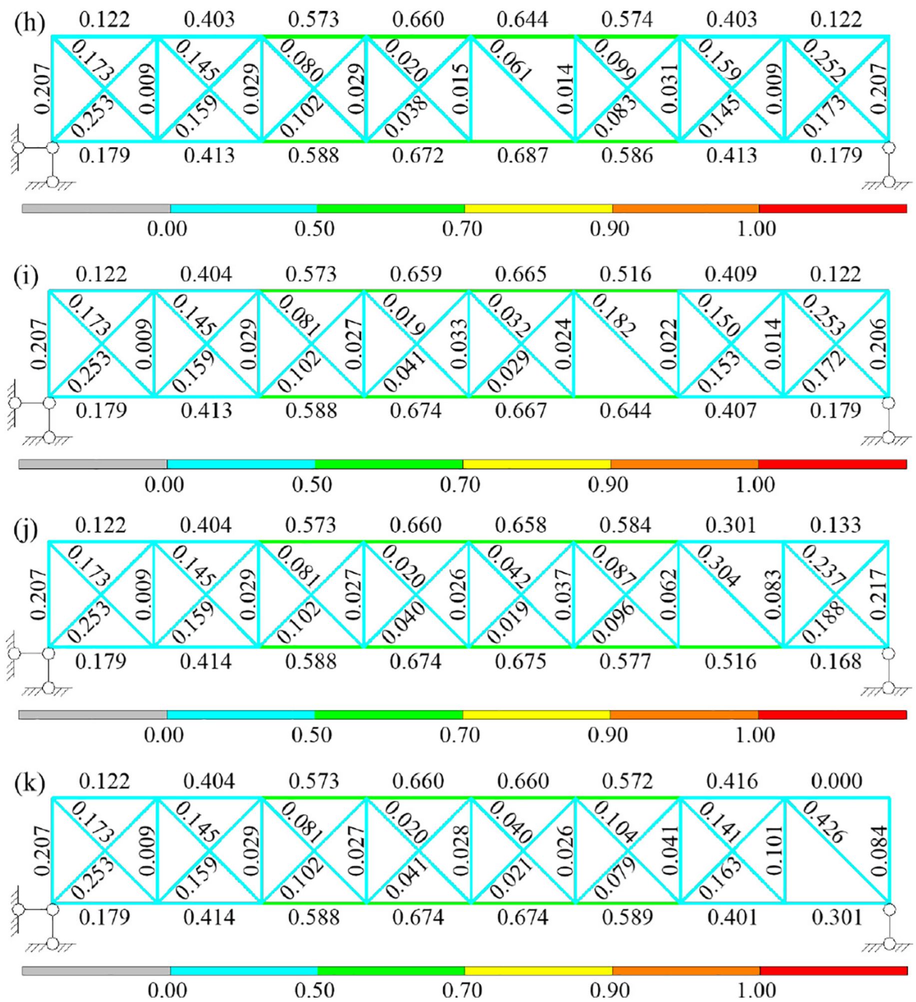


Fig. 4 (*continued*).

and 97% of the results exceeded 0.45. Therefore, the limit value of the collapse index for steel truss structures in fire can be conservatively set as 0.45.

4. Development of the monitoring system

The monitoring system is to be installed on an existing monitoring station of the fire control center. After completion of the structure, the initial structural information, including the geometric dimensions and the internal forces, will be stored in the database in advance. When a fire occurs, the temperature sensors installed on the structure can send the real-time temperature data to the station, and the software can directly evaluate danger levels of the components and the overall collapse index of the structure based on the pre-stored structural information, so as to achieve the purpose of fire safety monitoring.

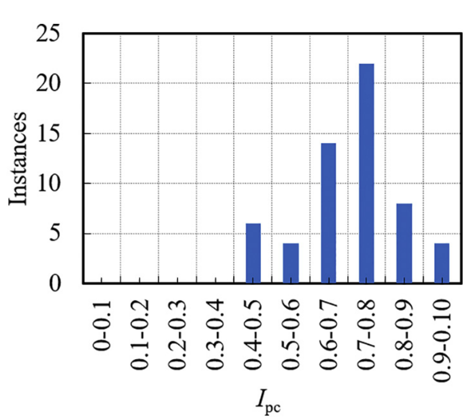


Fig. 5. Summary of collapse index distribution of steel truss.

4.1. Theoretical framework

The theoretical framework for the safety monitoring system of steel truss in fire can be described as follows:

(1) Preparation Step

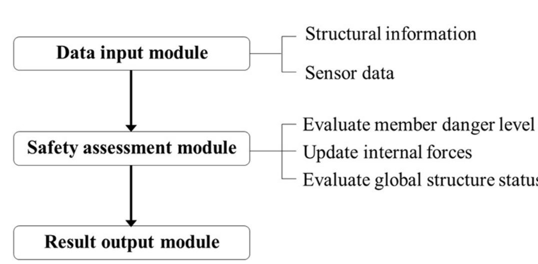


Fig. 6. System modules and functions.

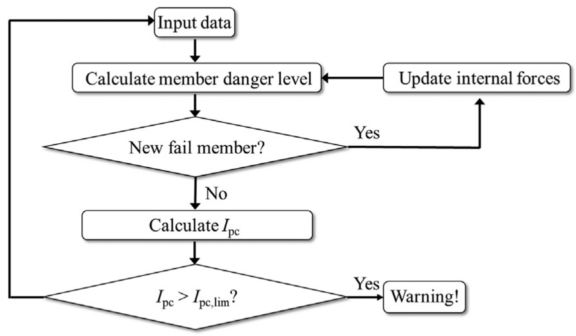


Fig. 7. Design of the module of safety assessment.

Input the information of the structure, including the geometric dimensions, boundary conditions, load conditions, et al. Based on the structural information, calculate the importance coefficient of each member, and arrange the temperature sensors according to the cost, the fire separation zones, and fire risk.

(2) Step 1

Calculate the member failure index according to Section 2.2;

(3) Step 2

Remove the most dangerous member(s) and calculate the internal forces.

(4) Step 3

Calculate the collapse index according to Section 2.3.

4.2. Design of the system

In order to realize the functions mentioned above, there exist several requirements for the system:

(1) A concise and complete user interface is needed, which can display the information such as the real-time member danger levels in fire and the overall structural status;
(2) A stable and responsive database is needed;
(3) The system should be compatible and universal to ensure stable operation on various platforms.

Therefore, the database is established in SQL Server 2017, and the user interface is written in the Visual Basic language. The system is compiled in Microsoft Visual Studio 2017. The modules of the system and their functions are shown in Fig. 6. The main module of the system is the safety assessment module, and its flow chart is shown in Fig. 7. Note that the current software can be operated stably on various versions of Microsoft Windows, which is one of the most commonly-used operating systems worldwide, while the software with the same principle is to be compiled for other operating systems, including MacOS and Linux.

4.3. User interface

The user interface of the system operation process is shown in Fig. 8, which can be divided into the display area, the operation area, and the warning area.

The left side of the display area is the catalog tree. The stored information, including the dimensions of the structure, members, joint loads, member loads, as well as the structural response information including displacements, internal forces, and temperatures can be requested to be displayed on the right side, by clicking the corresponding labels.

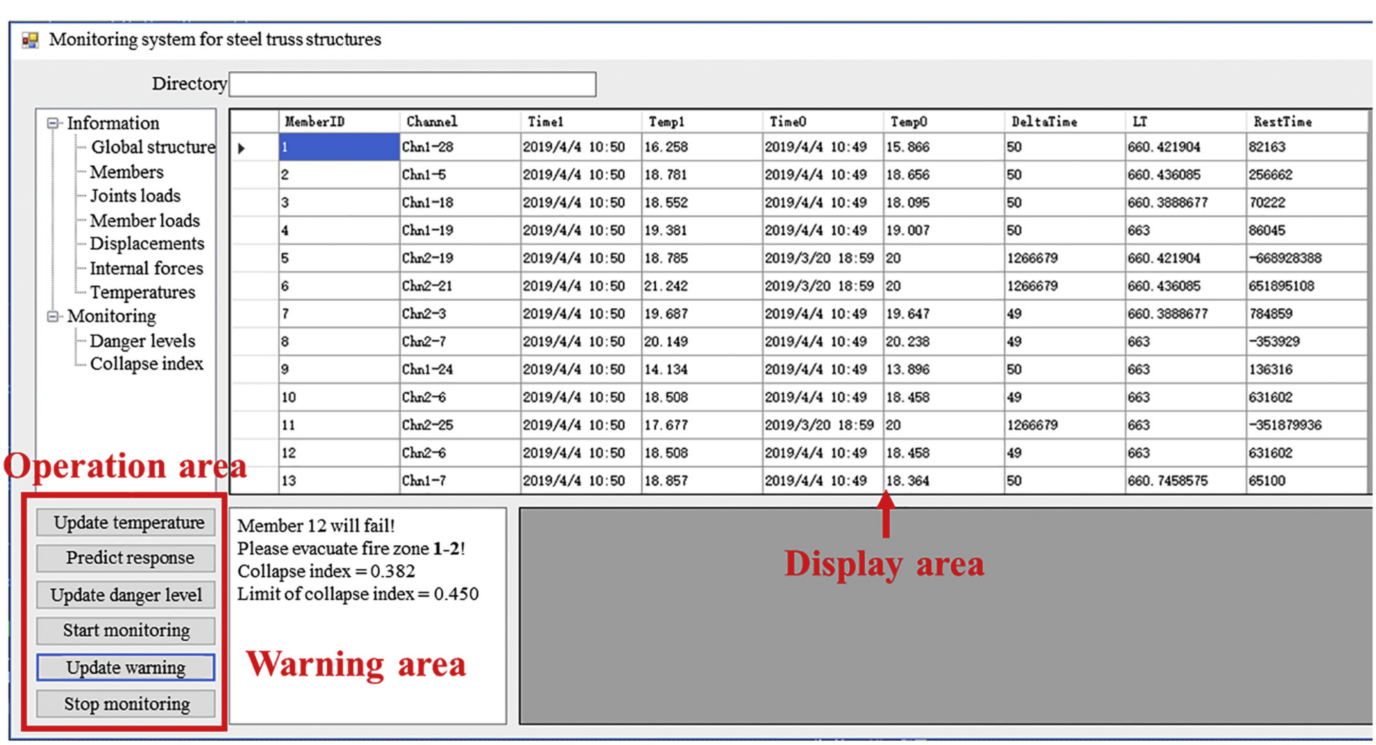


Fig. 8. User interface of the fire monitoring system.

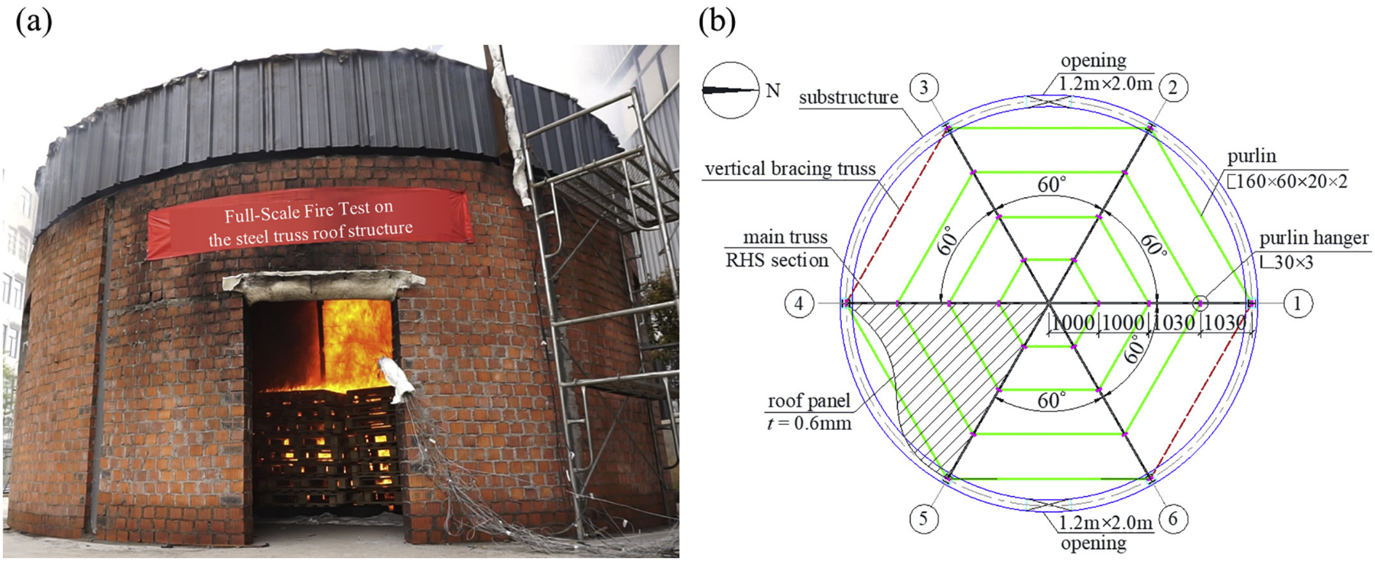


Fig. 9. Overall configuration of the test model [9]. (a) Overview. (b) Planar view.

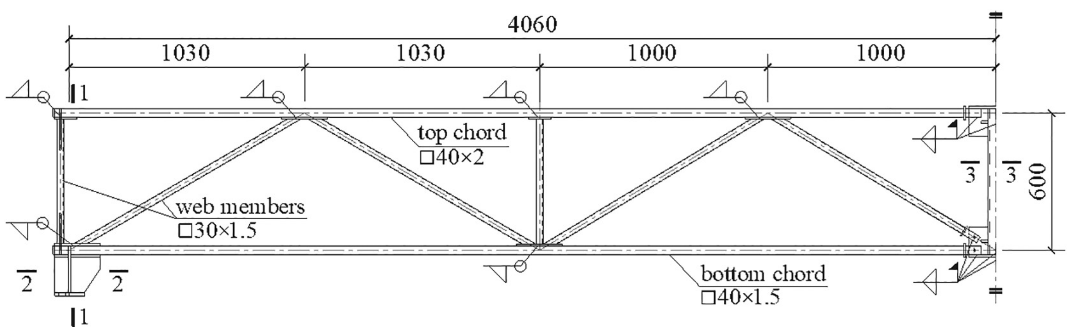


Fig. 10. Details of the main trusses [9].

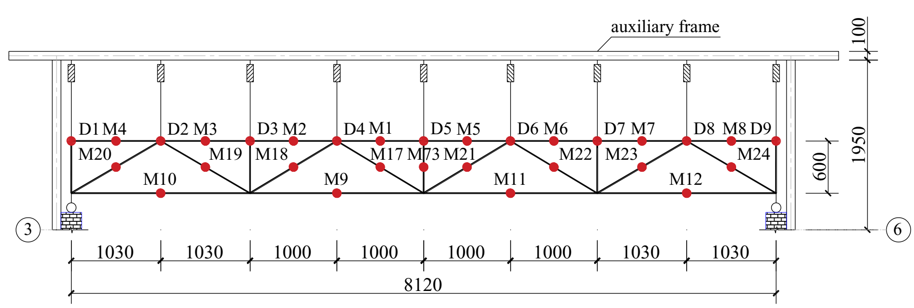


Fig. 11. Sensors for structural components.

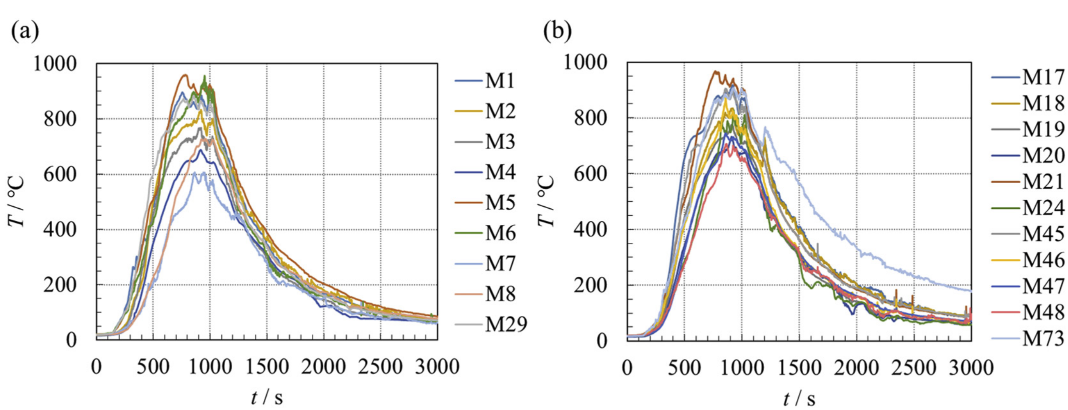


Fig. 12. Member temperature-time curves obtained in the test.

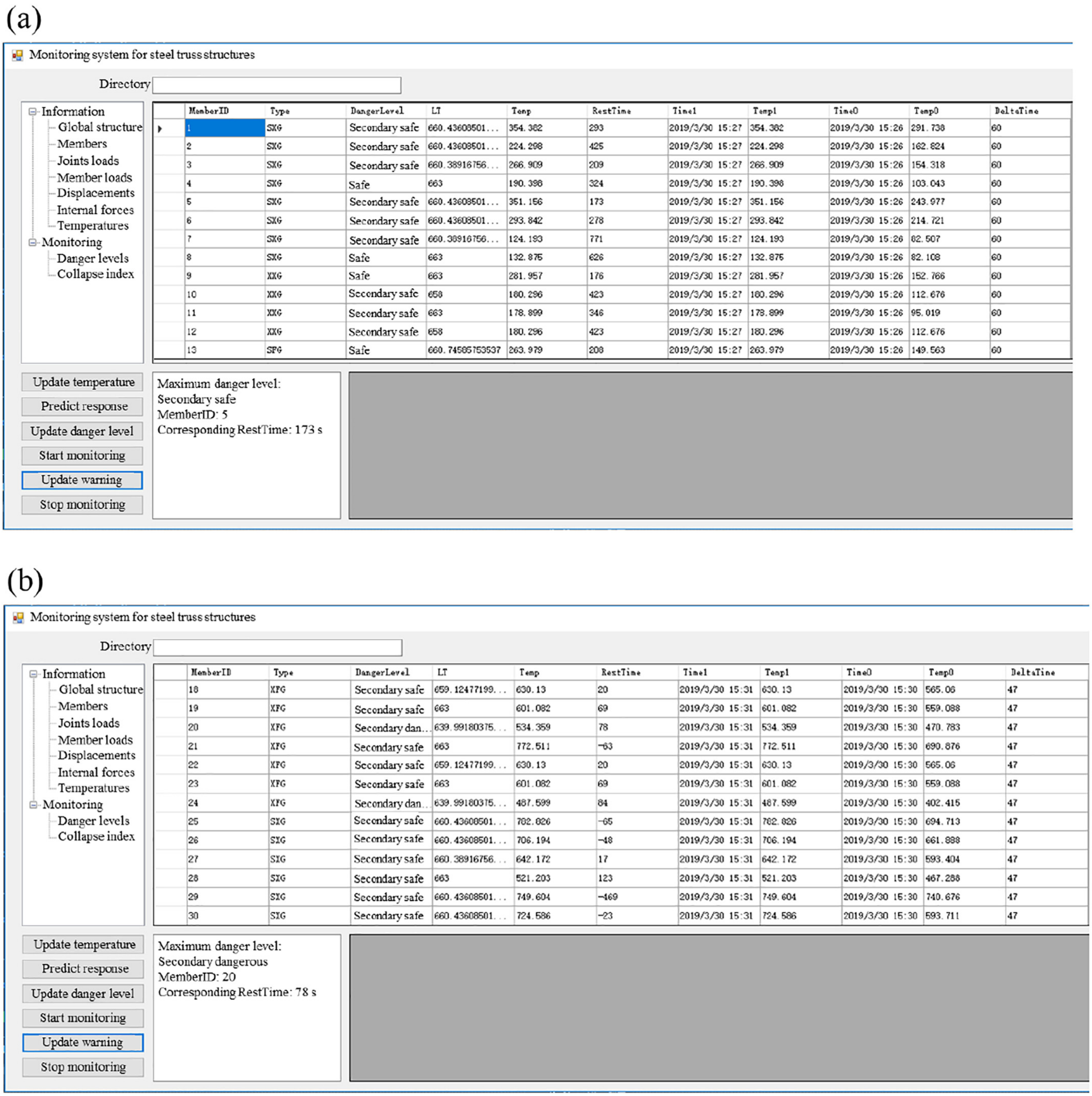


Fig. 13. System output results at various times. (a) 590 s. (b) 636 s. (c) 665 s. (d) 695 s.

In the warning area, the warning of the most dangerous member, which is about to fail, will be given. Besides, the corresponding collapse index and its limit value will also be given.

In the operation area, there are the six main function buttons of the system, including:

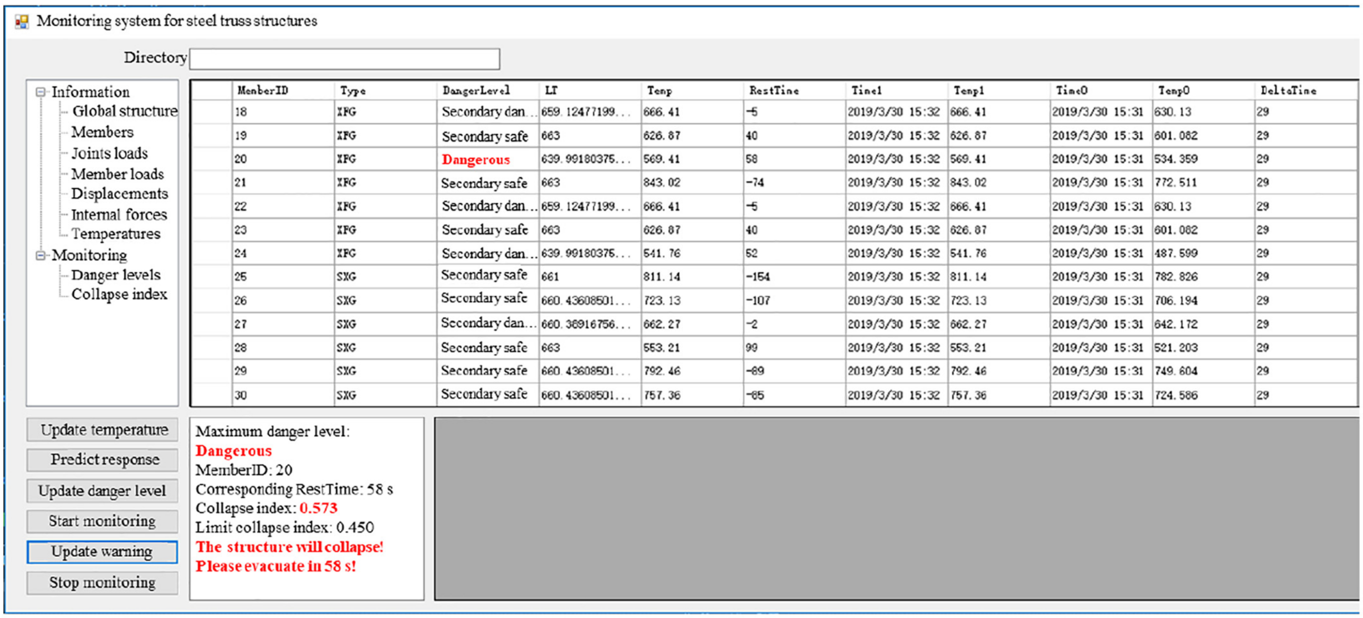
1) Start monitoring

After clicking this button, the system starts to operate automatically according to the process illustrated in Fig. 7. Firstly, the system will read the temperature input data from the sensors at regular intervals set by the user (default by 60 s). Secondly, the built-in function will be called to calculate the member danger level, and the member that is about to fail will be recognized and warned. Then, the system will assume the failure of the member by removing it from the structure, and update the internal forces and displacement data of the structure. Finally, the collapse index is calculated and displayed in the warning area.

2) Stop monitoring

After clicking this button, the system will enter the manual operation mode, in which the user needs to click the buttons to enable its function. Due to the variety of fire situations on-site, the manual mode is added to facilitate users to use the functions according to the actual situation.

(c)



(d)

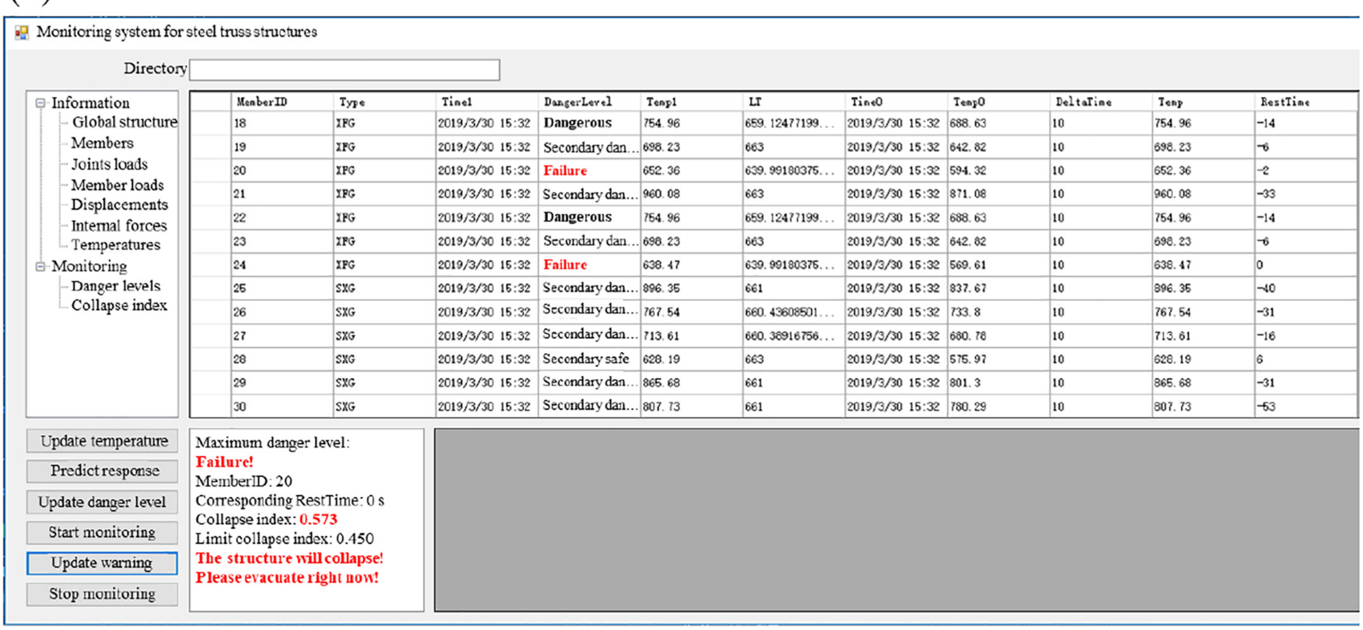


Fig. 13 (*continued*).

3) Update temperature (Manual operation button)

After clicking this button, the system will immediately read the temperature data from the sensors.

4) Predict response (Manual operation button)

After clicking this button, the system will calculate the structural displacement based on the structural temperature and the elevated-temperature material properties.

5) Update danger level (Manual operation button)

After clicking this button, the system will calculate the danger level of all the members, and show the results in the display area.

6) Update warning (Manual operation button)

After clicking this button, the collapse index will be calculated and displayed in the warning area.

5. Experimental verification

5.1. Test program

The destructive fire test conducted by Jiang et al. [9] is used to test the monitoring system developed in this paper.

The test specimen, exhibited in Fig. 9, was a full-scale steel truss roof structure. The diameter of the structure was 8 m, and the total height of

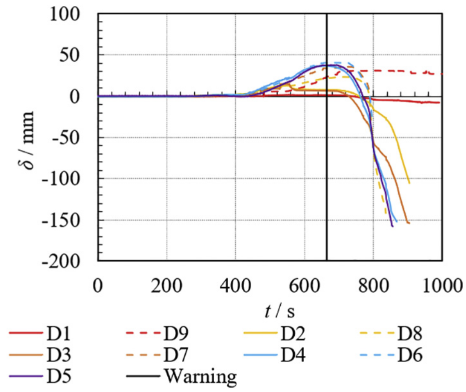


Fig. 14. Displacement-time curves in the test.

the test model was 4.02 m. The specimen was composed of six planar RHS (Rectangular Hollow Section) steel trusses, purlins and roof panels. The details of the main trusses are shown in Fig. 10. The specimen was loaded by iron sand buckets, and the designed surface was 0.439 kN/m^2. The test used wood cribs as the fuel, and the density of fuel was 20 kg/m^2. Due to the symmetry, thermocouples were placed on all the members of the truss at axes 3 and 6, and displacement sensors were used to record to vertical displacements of the joints, as shown in Fig. 11. Other details of the fire test can be found in reference [9].

5.2. Comparison of monitoring and test results

The member temperature-time obtained by the temperature sensors is shown in Fig. 12. It can be seen that the process of combustion can be classified into two stages, namely the initial growth stage (0 s ~ 650 s) and the stable combustion stage (650 s ~ 1100 s).

1) Initial growth stage

The fire test started at 15:21:00, denoted as 0 s. At 15:23:00 (120 s), the system output results showed that the member temperatures were at a low level. Although the temperature of some components rose to 45 °C, the calculated structural displacement was basically unchanged. At this time, all the members were at the "safe" level.

At 15:25:00 (240 s), the temperature of some members reached 176 °C, and its danger level changed to "secondary safe". However, the collapse index was close to zero, and the warning module did not make any response.

2) Stable combustion stage

At this stage, the fuel began to combust thoroughly, and the member temperatures rose rapidly. However, the initial stress ratios of the members were relatively low, so the majority of the members were still at the "secondary safe" level at 15:30:50 (590 s), as shown in Fig. 13a. However, the temperature of components was increasing very fast, and the system predicted that some "secondary safe" members would fail within 200 s (the "RestTime" column). With this information, the commander can grasp the time for the rescue.

At 15:31:36 (636 s), the temperature of some oblique web members reached 400 °C, and their danger level changed to "secondary dangerous", as shown in Fig. 13b. The prediction result indicated that there were only 78 s before the failure of the member No. 20. It is noteworthy that the temperature of some members had already exceeded their critical temperature (denoted as "LT"). This is because the critical temperature was calculated according to the Chinese code GB 51249 [19]. It is specified that for tensile members whose stress ratios are lower than 0.3, the critical temperature should be conservatively chosen as 663 °C. Since the internal forces have not exceeded their bearing capacity, their danger level did not change into "dangerous".

At 15:32:05 (665 s), the member No. 20 approached its critical temperature, and the corresponding danger level changed to "dangerous", as shown in Fig. 13c. The predicted time of failure was 58 s, at which time the firefighters should be advised to evacuate the corresponding area. When the danger level of a member changed to "dangerous", the system began to calculate the collapse index, and the result 0.573 exceeded the preset limit value 0.450, so warning of the collapse was also given.

At 15:32:25 (685 s), the danger level of members No. 20, No. 44, and No. 68 changed to "critical", and the minimum predicted time of failure was 30 s. Meanwhile, members No.24 and No.72 also changed to the "dangerous" level, which required special attention.

At 15:32:35 (695 s), the system indicated that failure occurred in members No. 20, No.24, No.44, No.68, and No.72, as shown in Fig. 13d. At this time, the structure might remain integral due to the ductility of steel, so the system was warning the commander to evacuate all the people as soon as possible.

The displacement-time curves of the structure are exhibited in Fig. 14. Note that the black line indicates the time of first warning, namely 665 s. At the warning time, the prediction of the structural response is given in Fig. 15, where the data of the displacement sensors at various times are also given for comparison. It can be seen that the global deformation of the specimen changed from arching to sinking, which indicated that the structure would collapse. The predicted displacement is the closest to the displacement at 845 s, which means the monitoring system could give the warning of the collapse location at least 180 s ahead of time.

Therefore, it can be concluded that the safety monitoring system can be helpful to give warnings about the location of the collapse (the failure member), which provides a reference to the commander to instruct the fire brigades, in order to avoid approaching related areas.

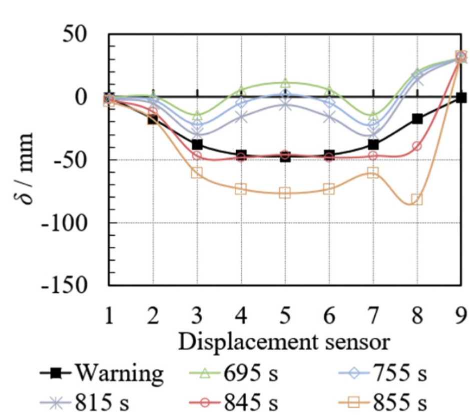


Fig. 15. Comparison of the predicted structural response and the test results.

6. Conclusions and expectations

The main conclusions of this paper are as follows:

1) The member importance coefficient is proposed based on the total strain energy, to roughly select the important members for arranging measuring points;
2) The member failure index for steel truss structures in fire is proposed based on the temperature, and six danger levels, including safe, secondary safe, secondary dangerous, dangerous, critical and failure, are proposed;
3) The collapse index for steel truss structures in fire is proposed based on the structural strain energy, and the limit value can be chosen as 0.45 according to numerical results;
4) A safety monitoring system for steel truss structures in fire is developed to evaluate the real-time structural safety and predict the collapse, which can provide a reference for the commander to instruct the fire brigades;

5) By comparing the output and early warning results of the safety monitoring system with the experimental phenomena and results, it is found that the monitoring system can reflect the failure of the members, and predict the overall structural response. The collapse prediction can be provided at least 180 s ahead of the collapse.

However, though the system was tested using the experimental data, and was envisaged to be helpful, further verification by evacuation experiments and numerical simulations will be conducted to raise the reliability of the system, before its application to real structures.

Declaration of Competing Interest

None.

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