Intelligent Fire Resistance Testing and Calculation of Precast Modular House by Computer Numerical Simulation

Qian Zhao[1, *], Yuliang Qi[1, a], Chuqi Shi[2, b], Keke Huang[2, c], Zhuchun Huang[2, d]

[1]Guangzhou Research Institute of Construction Industry Co., Ltd. Guangzhou, China

[2]Guangzhou Construction Engineering Co., Ltd. Guangzhou, China

* Corresponding Author Email: zhaoqian1987@126.com, [a]cupid.7@163.com, [b]chuqishi@163.com, [c]hkkate@126.com, [d]940687836@qq.com

Abstract. Through the fire resistance tests of fourteen components and one full-scale flat-packed modular house, the fire resistance limits of both steel components under standard fire curve and modular house entirety under real fire were studied. Test results showed that the fire safety could be guaranteed for applying light steel modular houses in low-rise buildings. In addition to structural fire protection design, fire performance simulation should also be combined with the measures of smoke alarm, spray, smoke diffusion simulation, evacuation simulation, fuel control and rescue response to ensure the fire safety. The research results of this paper can provide references for fire protection design of light steel modular houses.

Keywords: precast, full-scale, flat-packed modular house, fire resistance test.

1. Introduction

Modular Integrated Construction (MIC) is a highly integrated fabricated building form, which is the product of the development of construction industrialization [1-3]. As a kind of modular steel building, light steel modular house (commonly known as flat-packed modular house) has the advantages of light weight, high strength and convenient installation. Flat-packed modular houses have long been used in temporary buildings, which have no requirements for fire resistance. However, influenced by COCID-19 in recent three years, flat-packed modular houses have been applied in many emergency projects [4-7]. Because of the importance of these projects, the fire resistance of flat-packed modular houses becomes a focus of attention [8,9]. At the same time, with the development of MIC technology, the application scene of flat-packed modular houses gradually expands. Therefore, the research on the fire resistance of flat-packed modular houses has extremely important practical significance.

In this paper, through the fire resistance tests of 14 components and a full-scale flat-packed modular house, the fire resistance limits of the components under the standard fire curve and the performance of modular house entirety under real fire scene were studied. The experiment results showed that the fire resistance limits of the steel components cannot meet the relevant requirements of permanent buildings which are ruled in the code for fire protection design of buildings(GB 50016-2014)[10], since the cold-formed thin-walled structure was adopted in the modular houses. However, the fire resistance limits of the components with fire prevention measures could be greatly improved. In real fire scene, structural damage didn’t occur under certain fire loads, which proved that flat-packed modular house could be applied in three-story buildings. The research results of this paper can provide references for the fire resistance design of light steel modular houses.

2. Project profile

A COVID-19 emergency project is designed as a three-layer flat-packed modular house structure. The project is defined as temporary building for 5 years. The fire prevention requirements are as follows: the fire resistance limit of structural components should be able to meet the requirements of personnel safety evacuation and provide necessary conditions for fire rescue. The typical building layout of the project is shown in Fig. 1.

Cold-formed thin-walled steel and sandwich panel walls as non-combustible materials are adopt in the main structure. The indoor sides of loading structural components exposed to fire are protected by fireproof coatings or fireproof boards. Specific design requirements are as follows.

1) The ceilings, walls, ground substrates of passenger rooms and open-styled emergency stairs are made of decoration materials with combustion performance of grade A.

2) The combustion performance of ground surfaces should not be less than grade B1. The fixed furniture, decorative fabrics and partitions in the rooms are furnished with decorative materials of combustion performance not less than B2 level. The carpets should not be laid in the rooms, and all fixed furniture should be treated with flame retardant.

3) The combustion performance of lighting lamps should not be less than level B1. Distribution boxes, control panels, junction boxes, switches, sockets, etc., should not be directly installed on decoration materials with combustion performance less than B1.

Figure 1. Typical building layout

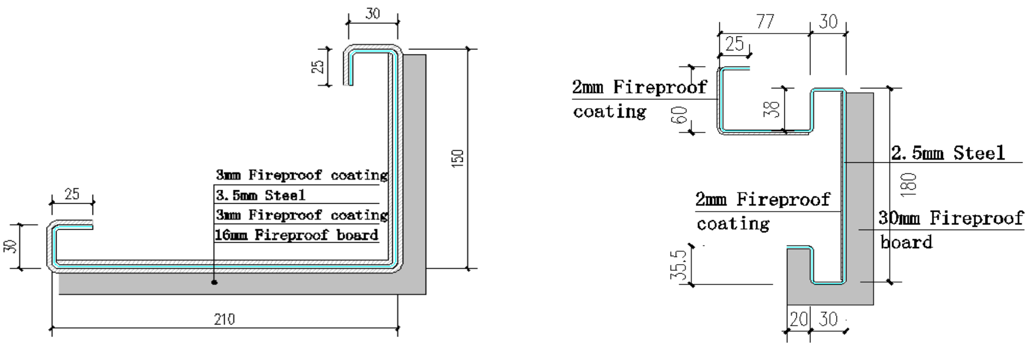
3. Fire resistance test of components

3.1. Component Design

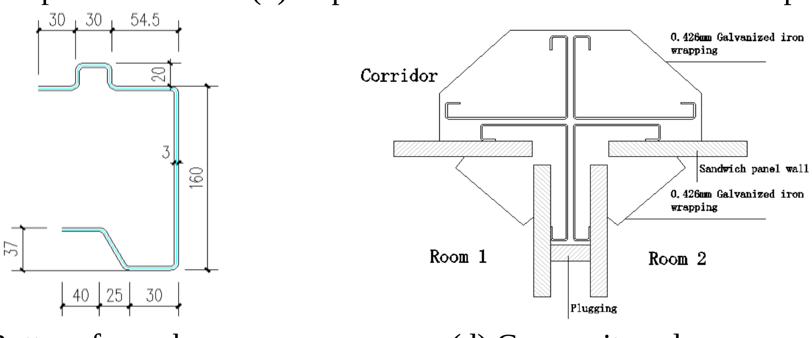
A total of 14 steel components were designed for fire resistance limit tests under standard fire curve which follows the code GB/T 9978-2008[11], including 3 beams, 4 walls, 3 columns, 2 stair flights, 1 ceiling and 1 floor. 8 components had no fire protection as comparison specimens, and 6 components adopted fireproof paint or fireproof board. The thickness of fire-proof layers was decided considering material properties shown in material refractory form report .Because only the situation of indoor fire was considered, the indoor surfaces of components took the fire prevention measures consistent with the actual. In order to get close to the real fire scene, the non-fire surfaces of beams and columns were protected by fire-proof boards in the experimental furnaces during the tests. Loading values of beams, columns and floors were taken as designed standard values. The specific structure is shown in Table I and Fig. 2. It should be noted that the wallboard structure is 0.426mm color coating plate + 75mm rock wool + 0.426mm color coating plate, the ceiling structure is 0.55mm color coating plate + 100mm glass wool + 0.42mm pressed aluminum-zinc color coating plate, and the floor structure is 1.6mm PVC floor leather + 18mm cement fiberboard + steel frame.

Table 1. Structure of components

No.	Classification	Name	Testing Item	Sample Size and Fire Mode	Structure	Explanation
1	Wall	Firewall	Vertical fire resistance limit test of non-bearing wall	Height × width: 2.53m × 3m Fire mode: One-side fire	Wall+30mm fireproof board (fire side)	Integrity Heat insulation
2		Wall of stairwell			Wall+20mm fireproof board (fire side)	
3		Wall of evacuation corridor			Single-layer wallboard	
4		Room partition wall			Double-layer wallboard+60mm air layer	
5	Column	Column without fire protection	Column fire resistance limit test	Height: 2.53m Load: 36.6kN for one column, 131.8kN for composite column Fixed mode: clamped support at both ends Fire mode: four side fire	L-shaped cold-formed thin-walled steel	Bearing capacity
6		Column with fire protection			Indoor surface: 3mm fireproof coating; Outdoor surface: 16mm fireproof board	
7		Composite column			Simulating the actual situation of four columns at the junction of rooms and corridor, 2mm fireproof coating is applied on the interior of the columns	
8	Beam	Top frame beam without fire protection	Beam fire resistance limit test	Length: 5.20m Load: 0.83kN/m for top beam, 2.49kN/m for bottom beam Fixed mode: clamped support at both ends Fire mode: three side fire	Cold-formed thin-walled steel	
9		Top frame beam with three-sided fire protection			Indoor surface: 2mm fireproof coating; Outdoor surface: 30mm fireproof board	
10		Bottom frame beam without fire protection			Cold-formed thin-walled steel	
11	Floor	Floor	Horizontal fire resistance limit test of load-bearing floor	Width × Length: 2.99m × 4.9m Load: 2kN/m^2 Fixed mode: quadrilateral simple support Fire mode: lower surface fire	Including the ceiling of first layer and the floor of second layer	Bearing capacity Integrity Heat insulation
12	Stair flight	Emergency stair without fire protection	Stair fire resistance limit test	Width × projected length × height: 1.2m × 2.516m × 1.448m, inclination angle: 30° Load: 3.5kN/m2 Fixed mode: simple support at both ends Fire mode: lower surface fire Installation mode: simulating actual inclination angle	Single steel stair flight	Integrity Heat insulation
13		Emergency stair with fireproof board			Stair flight with 30mm fireproof board on lower surface	
14	Ceiling	Ceiling	Ceiling fire resistance limit test	Width × Length: 2.99m × 4.9m Fixed mode: quadrilateral simple support Fire mode: lower surface fire	Including glass wool, steel beam and pressed color coating plate	



(a) Column with fire protection (b) Top frame beam with three-sided fire protection



(c) Bottom frame beam (d) Composite column

Figure 2. Structure of components

3.2. Test Equipment

The fire resistances of walls were tested in a vertical fire test furnace, and the maximum post-fire size of the equipment was 3.2m × 3.2m. The horizontal components such as beams, floors, emergency stairs and ceilings were tested in a horizontal fire test furnace, whose post-fire size was 3.0m × 4.5m and up to 4.8m for beams. The above equipment meets the requirements of GB UL EN BS ASTM standards. Columns were tested in a vertical component fire-resisting experimental furnace in the structural laboratory. The maximum vertical load is 500t, and the column length should be less than 3.0m. The equipment is shown in Fig. 3.

(a) Vertical fire test furnace (b) Horizontal fire test furnace (c)Column fire test furnace

Figure 3. Test equipment

3.3. Results and Analysis

3.3.1. Firewall

During the test, the fireproof board was connected to the wall by self-tapping nails. Before 55min, the initial section of the temperature rise curve of the non-fire surface was relatively flat. With the enlargement of the gaps caused by thermal deformations of fireproof boards, the temperature rose rapidly. During the whole process, the wall deformation rate increased continuously, and the maximum deformation at the geometric center was 64 mm. At 99min, the highest temperature of the non-fire surface of the specimen increased by 186.2℃, exceeding the standard limit, and the specimen lost the heat insulation. At 100min, the flame appeared on the back of the wall and lasted more than 10s, therefore the specimen lost the integrity (Fig. 4a).

After the firewall test, one piece of the fireproof boards fell off (Fig. 4b), the gaps between the fireproof boards were obvious, and the screws of the fixed fireproof boards fell off or broke. The shedding fire-proof boards had been pulverized and disformed after cooling.

(a) Continuous flame on the back at 100min (b) Fire side of specimen after test

Figure 4. Firewall test

3.3.2. Wall of stairwell

Before 40min, the temperature rise curve grew slowly. The maximum deformation at the geometric center was 20mm at failure. At 72min, the average temperature rise of the non-fire surface was 146.9℃, and the highest temperature rise was 180.4℃, which both exceeded the standard limit value. Thus the specimen lost heat insulation. At 75min, the cotton pad on the non-fire surface was not ignited, and continuous flames or overrun cracks were not appeared, therefore the specimen did not lose integrity.

3.3.3. Wall of evacuation corridor

The maximum deformation of failure at the geometric center was 63mm. At 23min, the highest temperature of the non-fire surface of the specimen increased by 187.1℃, which exceeded the standard limit, and the specimen lost heat insulation. At 24min, the flame appeared on the back of the specimen and lasted more than 10s, therefore the specimen lost the integrity of fire resistance. During the test, the heat transfer between the gap of wall boards was obvious.

3.3.4. Room partition wall

At 32min, the cotton pad on the non-fire surface was not ignited, and continuous flames or overrun cracks were not appeared. The specimen did not lose fire integrity. The average temperature rise of the non-fire surface was 17.5℃, and the highest temperature rise was 26.5℃. The specimen did not lose the heat insulation.

3.3.5. Column without fire protection

During the test, the upper and lower ends of the column were fixed on the loading system with high-strength bolts, which was consistent with the actual construction. Before 10min, the deformation of the column was presented as thermal tensile deformation. After 10min, the column was instable under compression and the deformation appeared as compression. At 13min, the maximum axial compression deformation of the specimen was 28.6433mm, the maximum axial compression deformation rate was 22.7415mm/min, and the specimen lost the bearing capacity.

3.3.6. Column with fire protection

At 35min10s, the maximum axial compression deformation of the specimen was 26.46mm, and the maximum axial compression deformation rate was 23.37mm/min. So the specimen lost its bearing capacity.

3.3.7. Composite column

The structure of composite column was designed to fully simulate the actual situation in the emergency project: the side in the corridor was surrounded by 0.426mm iron wrapping (Fig. 5a), and the other side simulated the spatial occlusion relationship between the interior walls, the columns and the iron wrappings (Fig. 5b). The wall sections were wrapped by aluminum alloy, and the gaps between the walls were blocked by rock wool sandwich plates. At 103min19s, the maximum axial compression deformation was 25.635mm, and the maximum axial compression deformation rate was 23.495mm/min. Thus the specimen lost its bearing capacity (Fig. 5c).

(a) Side in the corridor(before test) (b) Side in the room(before test) (c) Column after test

Figure 5. Composite column test

3.3.8. Top frame beam without fire protection

Beam components were loaded by four points on the top surface. At 15min10s, the bending deformation of the top frame beam reached 175.7mm, which was more than L/30. At 15min20s, the bending deformation reached 220.3mm, and the deformation rate of the specimen was 267.6mm/min, which exceeded the limit. Therefore the beam lost the bearing capacity.

3.3.9. Top frame beam with three-sided fire protection

At 70min20s, the bending deformation of the specimen reached 177.7mm, which was more than L/30. At 70min30s, the bending deformation reached 230.3mm, and the deformation rate was 315.6mm/min, which exceeded the limit. The specimen lost the bearing capacity (Fig.6).

(a) Load of beam

(b) Top surface protected by fireproof cotton

Figure 6. Beam test

3.3.10. Bottom frame beam without fire protection

At 10min30s, the bending deformation of the specimen reached 180.0mm, more than L/30. At 10min40s, the bending deformation arrived 216.6mm, and the deformation rate was 219.6mm/min, which exceeded the limit. Thus the specimen lost the bearing capacity. Since the bottom frame beam was completely coated in non-combustible materials such as cement fiberboard in practical engineering, and there was no exposed part, the fire resistance test of fireproof coating specimen was not carried out.

3.3.11. Floor

The floor specimen was tested with four-angle support (Fig. 7). The gap between specimen and furnace was sealed with inorganic mineral cotton, and a uniform load of 2kN/m2 was applied on the non-fire surface. At 32min, the specimen did not collapse or lose bearing capacity. The maximum bending deformation was 15.3mm and the maximum bending deformation rate was 1.3mm/min. The cotton pad on non-fire surface was not ignited, and no continuous flame or obvious cracks were found, therefore the specimen did not lose integrity. The average temperature rise of non-fire surface was 33.2°C, and the highest temperature rise was 48.4°C, which meant that the specimen did not lose the heat insulation.

Figure 7. Floor test

3.3.12. Emergency stair without fire protection

The stair was installed on a open-ended concrete frame while simulating actual inclination angle (Fig. 8). The upper and lower ends of the stair were simply supported on the frame, and two lateral sides of the stair were sealed with autoclaved aerated bricks. A uniform load of 3.5kN/m2 was applied on the upper surface, and the lower surface was subjected to fire during the test.

At 5min, the cotton pad on non-fire surface was not ignited, and no continuous flame or obvious cracks were found. The specimen did not lose fire integrity. At 3min, the average temperature rise of the non-fire surface was 165.1°C, and the highest temperature rise was 204.9°C, which exceeded the standard limit. The specimen lost heat insulation.

Figure 8. Stair flight test

3.3.13. Emergency stair with fireproof board

At 32min, the cotton pad on non-fire surface was not ignited, and no continuous flame or obvious cracks were found. The specimen did not lose fire integrity. The average temperature rise of the non-fire surface was 47. 0°C, and the highest temperature rise was 73.0°C. The specimen did not lose heat insulation.

3.3.14. Ceiling

At 14min, the cotton pad on non-fire surface was not ignited, and no continuous flame or obvious cracks were found. The specimen did not lose fire integrity. The average temperature rise of non-fire surface was 161.8°C, and the highest temperature rise was 182.6°C, which exceeded the standard limit. The specimen lost heat insulation. The maximum deformation of the span center was 81.2mm. The fire endurance of components are summarized in Table II.

Table 2. Fire endurance of components

No.	Classification	Name	Fire endurance/min		
			Bearing capacity	Integrity	Heat insulation
1	Wall	Firewall	/	100	98
2		Wall of stairwell	/	≥75	71
3		Wall of evacuation corridor	/	24	22
4		Room partition wall	/	≥32	≥32
5	Column	Column without fire protection	12	/	/
6		Column with fire protection	35	/	/
7		Composite column	103	/	/
8	Beam	Top frame beam without fire protection	15	/	/
9		Top frame beam with three-sided fire protection	70	/	/
10		Bottom frame beam without fire protection	10	/	/
11	Floor	Floor	≥32	≥32	≥32
12	Stair flight	Emergency stair without fire protection	/	≥5	2
13		Emergency stair with fireproof board	/	≥32	≥32
14	Ceiling	Ceiling	/	≥14	13

3.4. Summary

1) The cold-formed thin-walled steel structure is adopted in flat-packed modular houses, and the thickness of beams and columns is about 2.5mm to 3.5mm. The fire resistance limit time is short without prevention, which is not suitable for direct application in permanent buildings.

2) The fire resistance of steel components can be effectively improved with prevention measures. The fire resistance time increases by 3 times for walls with 3cm fireproof boards. While the column is coated with 3mm fireproof coating, the fire resistance time increases by 2 times. After the top frame beam is coated with 2mm fireproof paint, the time increases by 3.7 times.

3) However, limited to the structure, some members still cannot meet the fire resistance time requirements of permanent buildings under the standard fire test conditions. Compared with the relevant requirements of the third fire resistance level of permanent buildings in Chinese national code, the room partition walls, top frame beams with fireproof coating, floors, emergency stairs with fireproof boards and ceilings can satisfy the relevant requirements, and the fire resistance limit time of other components whiling taking protection measures is close to the required time. In the engineering, the requirements for fire resistance time of flat-packed modular houses should be determined in combination with the actual fire situation and the fire performance simulation.

4) While the sandwich panel wall is wrapped with fireproof boards, the fixation of the fireproof boards and the sealing of the gaps should be strengthened. The joint materials should have good expansion and fire resistance. It is maybe positive on extending the fire resistance limit of walls while the fireproof board is used as the core layer and not directly heated. The air layer between the double wall boards has positive effect on delaying heating.

5) The fire resistance limit time of the composite column is much larger than that of a single column, which shows that the fire protection effect of walls and iron wrappings on L-shaped steel columns is obvious.

6) Partial coating cracks and falls off after the test, which may be due to the poor compatibility between the coating and galvanized steel columns, or the nonstandard operation and maintenance in spraying process that result in poor adhesion of the coating. Adding bonding paint and increasing coating curing time may prolong the fire resistance limit time.

4. Full-scale flat-packed modular house fire test

The fire test objectives of full-scale three-layer flat-packed modular houses are as follows.

1) Obtain the development process and temperature data of indoor fire, as well as the heating process and displacement deformations of structural components in real fire scene. The fire resistance time and failure mode of the flat-packed modular house should also be recorded.

2) Observe the possibility of flashover and predict the evacuation safety in the typical interior furnishing arrangement.

4.1. Experimental design

4.1.1. Flat-packed modular house selection

According to the actual situation, the single room with largest fire load density was selected, and three-layer superposition structure was adopted. The size of the three-layer structure was 2.99m (W) × 6.055m (D) ×8.685m (H). A 2.69m×1.63m 6Low-E+12A+6mm hollow toughened glass was installed on one side of the flat-packed modular house, and a 1.0m×2.1m common door was installed on the other side. During the test, fire prevention measures such as fireproof paint or fireproof board were not taken. Furniture, fabric and other combustibles were arranged according to the actual layout in the first layer to fully simulate the real fire scene. Because there was no fire in the second and third floors, only the bottom assemblies, top assemblies and columns of the second and third floors were set up. Sand bags were piled to simulate the indoor load and roof load. Considering that the guests may carry luggage with clothes, two 20-inch suitcases filled with fiber fabric were placed beside the television. The typical layout and calorific value of combustibles in the first floor are shown in Fig.9 and Table III. Overall, there are not many indoor combustibles, and the fire load is small.

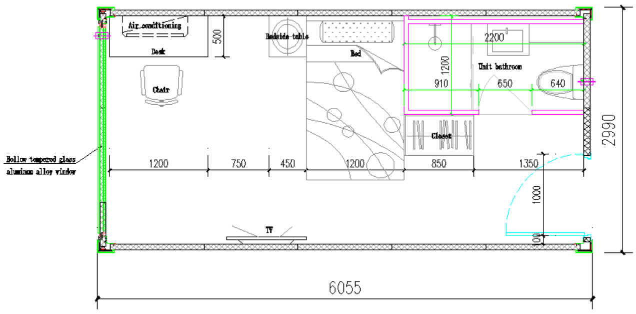


Figure 9. Typical inner layout

Table 3. Indoor combustible substance

No.	Combustible substance	Calorific
1	Bed	1600
2	Bedside table	160
3	Mattress	480MJ
4	Desk	250MJ
5	Chair	250MJ
6	Simple closet	200MJ
7	TV rack	300MJ
8	TV	150MJ
9	Air conditioning	150MJ
10	Curtain	$10MJ/m^2$
11	Bedding, clothes and other	17 ～

4.1.2. Ignition scheme

Due to the special provisions of the project, guests are not allowed to carry lighters, matches and other related ignition sources. In addition, ignited mosquito incense and other daily necessities that may cause fire are not allowed to use in the rooms. Therefore, after investigating the factors of fire, it is considered that the most likely type of fire is electrical fire, which is usually caused by short circuit of electrical appliances or during charging of mobile phones. The most dangerous and most likely situation is that the mobile phone is charged on the bed to cause fire. Thus the ignition method in the test is to make the mobile phone battery burn and explode on the bed through electric heating, so as to ignite the bedding articles. The iPhone cell is used in the experiment, whose rated capacity is 3.80V and 1980mAh. Nickel-chromium wire is used to ignite mobile phone battery. The diameter of nickel-chromium wire is 0.81mm, and the length is 150mm. The current is 13.9A during ignition, and the DC voltage at both ends of the wire is 35.4V.

4.1.3. Ventilation mode

For epidemic prevention needs, under normal conditions, the door of the room is in a long closed state, and only one window can be opened, with the maximum opening angle of 15 degrees. During the test, two conditions are considered. One state is to keep the doors and windows completely closed. The other is to open a window to 15°, and leave the door with a 1cm gap to simulate the situation of people escaping.

4.1.4. Determination of test load

According to the structural design, the test loads of the second and third layer are calculated as follows:

a) Permanent load of sandwich panel wall:

$0.12kN/m^2 \times (18\times3-2\times3)m^2=5.76kN$

b) Permanent load of glass window:

$1kN/m^2 \times 3m \times 2m=6kN$

c) Permanent load of bathroom: 400kg, i.e. 4kN
d) Permanent load of furniture: 500kg, i.e. 5kN
e) Permanent load of roof: 0.15kN/m2×3m×6m=2.7kN
The load on the second or third floor is (1)+(2)+(3)+(4)=20.76kN, i.e. 2076kg. The roof load is 270kg, i.e. 67.5kg on each corner fittings of the third layer. The loads are simulated by stacking sand bags in the tests as shown in Fig. 10.

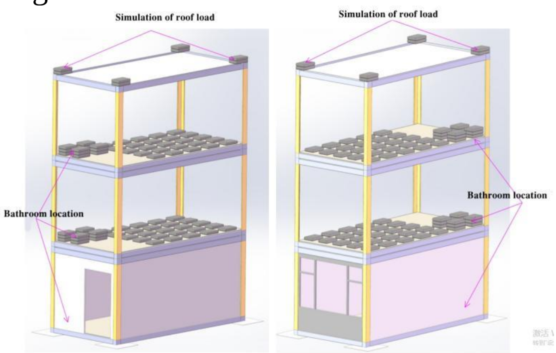


Figure 10. Load arrangement

4.1.5. Data collection

The major focus test data includes: the temperature in the room, the temperature of the main steel components, the deformation of the steel structure under the dual conditions of fire and stress.
The equipment contains thermocouples, displacement sensors, cameras, etc.
a) Thermocouple
The distribution of thermocouples is shown in Table IV.

Table 4. Thermocouple arrangement

No.	Stationing position	Quantity
1	Center of seed area (H=2.0m, 2.3m, 2.5m)	3
2	Combustion source surface, i.e. center and head of the bed	2
3	7 on inner surface and 5 on outer surface of the wall near bed	12
4	6 on inner and 4 on outer surface of the wall opposite the bed	10
5	3 on inner surface and 2 on outer surface of the wall beside the door	5
6	4 on inner surface and 6 on outer surface of the wall beside the window	10
7	6 on inner surface and 6 on outer surface of first floor	12
8	6 on inner surface and 6 on outer surface of first ceiling	12
9	3 on inner surface and 3 on outer surface of each column of first floor	24
10	2 on inner surface and 1 on outer surface of each short bottom frame beams of first floor	6
11	4 on inner surface and 2 on outer surface of each long bottom frame beams of first floor	12
12	2 on inner surface and 2 on outer surface of each short top frame beams of first floor	8
13	4 on inner surface and 3 on outer surface of each long top frame beams of first floor	14
14	4 on inner surface and 4 on outer surface of second floor	8
15	1 on outer surface of each short bottom frame beams of second floor	2
16	2 on outer surface of each long bottom frame beams of second floor	4
17	2 on outer surface of each column of second floor (H=0.5m, 1m)	8
18	5 thermocouple trees on the first floor, tree height=1.8m, one thermocouple at 0.6 m, 1.2 m and 1.8 m respectively	15
19	1 environmental temperature thermocouple at the position 1m from wall and 0.5m high	1
20	1 on each joints of beams and columns of upper frame	4
	Total	172

b) Displacement sensor
Four vertical displacement sensors with a range of 100~200mm are set at the top of four columns on the first floor. Two vertical displacement measurement systems with a range of 200~400mm are

set at the middle of two long-edge top frame beams. The axial deformation of four columns and the mid-span bending deformations of two long-edge top frame beams are measured respectively.

c) Camera

Two cameras are set to record the fire test process inside and outside the modular house.

4.2. Test results and analysis

4.2.1. Fully enclosed state

a) Test conditions

During the test, the weather was sunny. At the beginning of the test, the ambient temperature was 30.5°C, the humidity was 50%, the atmospheric pressure was 100.7kPa, and there was no wind (Fig. 11).

Figure 11. Flat-packed modular houses before test

b) Test process record

The test process is recorded in Table V.

Table 5. Process record of fully enclosed state test

Time (hh:mm:ss)	Process record
00:00:00	Started up data acquisition system and video recording system.
00:01:00	Began to heat the battery by electricity, current 13.9 A, voltage 35.4 V.
00:03:40	Fire was visible and bedding articles was ignited.
00:05:33	Ignition was stopped.
00:05:34	The burning on the bed was intensified, and obvious black smoke was produced.
00:06:13	The fire on the bed increased obviously.
00:06:32	Smoke in the first layer was significantly denser (Fig. 12).
00:06:50	Black smoke began to emerge at the door gap.
00:07:11	The camera in the first layer was almost completely occluded by smoke.
00:07:34	Black smoke emerged from the corners of the window and the gaps between the wallboard and top beams.
00:08:30	The camera in the room was completely blocked by smoke.
00:47:36	The black smoke began to emerge intermittently from the top of the window.
01:10:00	Test stopped.
01:10:46	The door and the window were opened to ventilate and exhaust smoke.

c) Test results

The whole test duration was 1h and 10min. The overall structure of the modular houses was normal, and the combustion area did not spread outside.

1) During the experiment, the mattress reached the highest temperature of 405.1°C at 14min, the ceiling surface above the mattress reached the highest temperature of 249.4°C at 9min, the floor under the bed reached the highest temperature of 58.8°C at 12min, the surface of the wall near the bed reached the highest temperature of 185.6°C at 11min, the surface of the wall opposite the bed reached the highest temperature of 132.8°C at 13min, the inside surface of the door reached the highest

temperature of 130.6°C at 10min, the inside surface of the window reached the highest temperature of 75.2°C at 14min, the inside surfaces of the columns of the first layer reached the highest temperature of 100.1°C at 10min, the inside surfaces of the top frame beams of the first layer reached the highest temperature of 101.1 °C at 12min, the floor of the second layer reached the highest temperature of 59.9°C at 68min, the outside surfaces of the bottom frame beams of the second layer reached the highest temperature of 49.6°C at 42min and the outside surfaces of the columns of the second layer reached the highest temperature of 44.1°C at 70min.

2) After 6min, there was continuous black smoke emerged from the top gaps and the door gaps of the modular house as shown in Fig. 13.

3) During the test, the maximum thermal expansion deformation of the columns was 0.3mm, and no compression deformation was found. The maximum downward deformation of the beams was 0.1mm.

4) After the test, a 1.2m×1.2m range combustion carbonization was found on the mattress. Smoke alarms arranged on the ceiling was burned down to the ground. The plastic shell of the air conditioning was partial melted as shown in Fig. 14. No abnormal was found on glasses of the window. Indoor tables, chairs, curtains, television and the luggage were not burned.

5) No fire extinguishing operation was carried out during the test, and the indoor fire was extinguished automatically.

Figure 12. 6min32s after start-up

Figure 13. 6min50s and 7min34s after start-up

Figure 14. Furniture after test

4.2.2. Local ventilation state

a) Test conditions

During the test, the weather was sunny. At the beginning of the test, the ambient temperature was 37.9°C, the humidity was 39%, the atmospheric pressure was 100.4kPa, and the wind speed was 0.6m/s.

b) Test process record

The test process is recorded in Table VI.

Table 6. Process record of local ventilation state test

Time (hh:mm:ss)	Process record
00:00:00	Started up data acquisition system and video recording system.
00:01:00	Began to heat the battery by electricity, current 13.9 A, voltage 35.4 V.
00:02:47	Fire was visible and bedding articles was ignited.
00:03:23	Alert was sent out by smoke alarm.
00:03:35	Ignited bedding articles started dripping from the edge of the bed to the floor.
00:04:09	The burning on the bed was intensified.
00:04:10	Black smoke began to escape from the opened door and window.
00:04:33	Ignition was stopped.
00:04:53	Smoke in the first layer was significantly denser.
00:05:15	The combustion on the bed was further intensified, and the amount of smoke emitted at the door gap increased.
00:05:28	Indoor combustion observation had been almost impossible through the camera because of the smoke.
00:07:19	A lot of black smoke continued to emerge from the open door and window.
00:12:18	The temperature data showed an upward trend of indoor fire.
00:43:00	The temperature data showed an downward trend of indoor fire.
00:53:16	The emitted amount of black smoke increased.
01:05:23	The temperature data showed an downward trend of indoor fire again.
01:39:06	The overall indoor temperature of the first floor decreased significantly.
02:01:00	Test stopped.
02:01:19	The door and the window were opened to ventilate and exhaust smoke. The bed, bedding articles, luggage, curtains, air conditioning were almost burned out and the window was not broken as shown in Fig. 15.

c) Test results

The test time was 2h and 1min, the overall structure of the modular houses was normal, and the combustion area did not spread to the outdoor.

1) During the test, the highest temperature on the mattress reached 715.8°C at 22min, the highest temperature on the ceiling surface above the mattress reached 430.8°C at 54min, the highest temperature on the floor under the bed reached 527.4°C at 90min, the highest temperature on the surface of the wall beside the bed reached 549°C at 83min, the highest temperature on the surface of the wall opposite the bed reached 348.3°C at 51min, the highest temperature on the inside of the door reached 332.9°C at 50min, the highest temperature on the inside of the window reached 267.2°C at 51min, the highest temperature on the inside of the columns of the first layer reached 230.2°C at 58min, the highest temperature on the inside of the top frame beams of the first layer reached 251.9°C at 56min, the highest temperature on the second floor reached 62.9°C at 100min, the highest temperature on the outside of the bottom frame beams of the second layer reached 96.6°C at 63min and the highest temperature on the outside of the columns of the second layer reached 50.7°C at 72min.

2) After 4min, black smoke continued to emerge from the opened window and door.

3) During the test, the maximum thermal expansion deformation of the columns was 0.9mm, and no compression deformation was found. The maximum downward bending deformation of the beams was 0.8mm.

4) No fire extinguishing operation was carried out during the test period, and the indoor fire was extinguished automatically.

Figure 15. Bed and luggage after test

4.3. Summary

1) In these two tests, there is no flashover phenomenon occurred, and the structure of the modular houses is not obviously deformed. The reasons are that there are not many combustible matters in the room and the total calorific value is not high. At the same time, limited air flow limits the development of fire. Even if that the steel components are not coated with fireproof paint, the fire does not have a great impact on the steel beams and columns which are protected by the wrappings and walls.

2) In the local ventilation state, the fire development speed is faster than that in the fully closed state, and the indoor temperature significantly increases. However, due to the limited oxygen supply in the later period, the fire does not spread.

3) The smoke alarm device can alarm within 1min, which is helpful to the rapid evacuation of passengers.

5. Conclusions

Through the fire resistance test of steel components and full-scale flat-packed modular house, the basic fire safety can be ensured for applying light steel modular houses in low-rise buildings. At the component level, fireproof coating or fireproof board can effectively improve the fireproof performance of modular houses. In addition to structural fire protection design, fire performance simulation should also be combined with the measures of smoke alarm, spray, smoke diffusion simulation, evacuation simulation, fuel control and rescue response.

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