Full-Scale Standard Fire Experiment and Numerical Modelling Behaviour of Non-Load Bearing Calcium Silicate Partition Drywall

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Abstract. The study uses the non-load bearing calcium silicate partition drywall as the test specimen, with full-scale standard fire test and the CFD finite element numerical modelling simulation on 300 cm × 300 cm area specimen. The whole process of experiment fire test and the numerical modelling simulation result is highly correlated. This numerical modelling simulation can be applied to other researches on the other wall systems. This is an innovative and valuable research. Since they are highly correlated, the CFD finite element numerical modelling can be processed to work out the predicted results before the test, which can greatly save the cost of test. When the predicted results is satisfying, the standard fire test can be processed to verify the results.

1. Introduction
The firewalls installed in fire compartment should be possessed of flame retardant effectiveness to limit fire growth and forestalling structural failure. But whether the building component reach the fire resistance, is requires to be testing with the standard furnace fire. This approach, leading to a ranking of products as a function of the building materials and structures behaviour under a standard fire exposure is use in a lot of countries. (e.g. NFPA 251[1], ISO 834-1[2] and CNS 12514[3]). Nowadays, various countries have adjusted the specimen sizes of firewall to at least more than 3m high and 3m wide. For the trend of building engineering is towards increasing in dimension and high-rise, the conventional heavy building materials and high labour intensive methods are descending. For example, different non-load bearing drywall systems which are expected to replace the traditional thick and heavy building materials appear constantly. These systems have features of optimization constructional methods, shortening the constructional duration, various constructional methods, light materials and the quality is more stable than concrete. The surface of the non-load bearing partition drywall is boards. Generally, there are calcium silicate boards, gypsum boards, cement board and magnesium oxide boards, with light steel frames of 0.8mm~1.2mm serving as the supporting framework. Between two plates, the common rock wool of 60kg/m³~100kg/m³ are stuffed.

There are many researchers study on the performance issues of non-load bearing partition drywall. Chuang et al. [4] had proposed influences exerted by the environmental temperature during the relevant firewall tests on the specimen temperature of the non-fire exposure side. Collier and Buchanan [5] conducted researches related to the fire rating of constitutions of partition walls. Ho and Tsai [6] proposed that the quality of boards had a great effect on the fire resistance of wall. Wang et al.
[7] once proposed that installing devices, such as embedded junction box in the wall could influence the fire resistance of the wall. The above researches are focus on the fire resistance of non-load bearing drywall based on a standard fire test experiments. With CFD (Computational Fluid Dynamics) is increasingly applied in various engineering fields, numerical simultaneous aided researches in building field by making use of CFD is becoming widespread. For example, Do et al. [8] came up with that the thermal conductivity of porous material is mainly related to the thermal conductivity of its components and spatial arrangement of its complex structure by formula, microstructure observation and experiments. At present, there is no study focus on comparison of the performance of calcium silicate drywall by full-scale standard fire experiment and numerical modelling, which this research will study on it. The research will use quantitative analysis of a fire resistance through a standard fire test experiment and CFD numerical modelling. Aim to explore the correlation between the full-scale standard fire test and CFD numerical modelling simulation. The test uses the standard in ISO 834-[2] to perform on a test specimen which size is 300cm (width) × 300cm (height). Proposed the numerical model to simulate the process of transient heat transmission, compare the results of computer simulation and the test results.

2. Test methodology

2.1. Standard test furnaces
In this research, the test equipment is applied and can conduct material testing horizontally or vertically. The standard test furnace of equipment is 300cm (width) × 300cm (height) × 240cm (depth). The furnace adopt the electronic ignition and the control system is the computer PID temperature controller. There are 8 burners in the furnace which only 4 are switched on for wall test. Ceramic wool with a thickness of 300mm and a density of 160 kg/m³ was paved within the furnace. The furnace floor was composed of firebricks (size: 230mm× 114mm× 65mm) and gaps among firebricks were coated with refractory mortars. Such bricks were evenly allocated in nine thermocouples furnaces (Type K) (the distance from the fire exposure side of specimen was 100mm) (see figure 1), and 2 furnace pressure meters and T-type pipes (the heights of T-type pipes were respectively equal to the 150 cm and 250cm from the bottom of furnace). At the back of the furnace, there is an air outlet for exhaust air and it is connected to the outdoor chimney. All thermocouples are 10cm away from the fire testing area of specimen. The temperature in the furnace is measured by K-type thermocouple of which specification conforms to the regulation of CNS 5534 [9] that the thermocouple shall possess property above 0.75 Grade. The heat-resistance stainless steel pipe is placed in the insulated stainless steel pipe of which inner diameter is 14mm and front end is open and the hot junction of front end extrudes 25mm. All thermocouples in the furnace have been placed in the environment of which temperature is 1000°C for 1 hour [2] before the first use to increase the sensitivity of measuring the temperature and the accuracy requirement is ±3%. The Type K thermocouples in furnaces and Type K thermocouples on the un exposure side of the specimen utilize the compensating lead wires of thermocouples to connect to the data miner.

Figure 1. Full-scale standard fire test furnace and location of furnace thermocouples.
The data miner is made by Japanese YOKOGAWA Company. All equipment signals will firstly connect to DS 600 data recorder. And then, DS 600 will deal with the signals before transferring them to DC 100. In the end, the signals will be converted to output to the computer. In the test, the researcher heated the specimen respectively based on the heating curve of ISO 834-1 [2] standard. The relationship formula between temperature and time is shown as below:

\[ T = 20 + 345 \log_{10}(St + 1) \]  

where

\( T \) is the average furnace temperature, in degree Celsius; 
\( t \) is the time, in minutes.

2.2. Test specimen materials

Thickness of specimen framework is 15cm and the framework welded with steel plates of 5mm thick. Its inner part is made of concretes with 210kg/cm\(^2\) compressive strength. In the concretes, juxtapositions of spot welding reinforcing mesh with a diameter of 5mm and an interval of 150mm are set. The specifications conform to CNS 6919 [10]. In short, specimen frameworks and the contact surfaces of specimens shall be similar to the practical installation situations to the greatest extent. Test materials including light steel frames, rock wool, calcium silicate boards. As to the C-type internal framework, the size is 65×35×0.8mm@406mm. The size of C-type peripheral framework is 67×30×0.8mm. The size of flying shore is 38×12×1.0mm@1200mm. The thickness and density of rock wool is 50mm and 60kg/cm\(^3\) respectively. The calcium silicate boards conforms to provisions of the first level, with white colour, a thickness of 9mm, a density of 1.31 g/cm\(^3\). The thickness of wall being composed of all materials is 83mm. Test materials are shown as figure 2, figure 3. As the test expects to study the similarity of results of numerical modelling and test.

2.3. Record the temperature of the test specimen

Test sets 8 thermocouples on the unexposed surface of the specimen, as shown in figure 4. According to the requirements of the ISO 834-1[2], it observes the temperature distribution. Because it is required
to compare the similarity of results of numerical modelling and tests as well as optimize the computer model, three measuring points are set in the middle layer of wall and measuring positions are respectively in the position of 9mm, 41mm and 74mm, as shown in figure 5. The temperature measurement is recorded once every 6 seconds by computer and recorded by photos during the test.

**Figure 4.** The position of test thermocouples.

**Figure 5.** Cross-section of the wall with indication of the Thermocouple position in the Test.

3. Numerical modelling methodology

3.1. General modelling

In this research, the numerical modelling takes the Finite Element Numerical Analysis of which principle is to divide the solution domains to several interrelated sub-domain units, assume a proper approximate solution to every unit, deduce the general satisfied conditions of the domain and work out the solution of the question. Numerical modelling is based on CFD technology for a series of computer simulation analysis, the use of software Fluent to solve. It can be roughly divided into three parts: Pre-Processing, Solve and Post-Processing. Pre-Processing mainly focuses on how to build geometric model and mesh. This research needs to get the computer model which matches the standard fire test result, so the geometric model is corresponding with the standard fire test of specimen. Therefore, it’s necessary to build the geometric model, and mesh it into several units. Based on the shape and size of building components, the test meshes it by hexahedron. The meshing size of calcium silicate board, steel stud and fireproof cotton are respectively 9×9×9mm, 0.6×0.6×5mm and 5×5×5mm, as shown in figure 6. Solve mainly includes how to set up the related material parameters,
set boundary conditions and select the mathematics model and calculation methods. Post-Processing aims to analyze the data solved by modelling.

**Figure 6.** Numerical model of meshing.

### 3.2. Parameter setting

The materials used in the test include steel, calcium silicate board and rock wool. The parameters involved in modelling material are specific heat (J/kg°C), Thermal conductivity (W/m°C) and Density (kg/m³). Parameters used in steel refer to the regulations of BS EN 1993 [11]. In addition, the specific heat of steel linearly increases as the temperature rising, as shown in figure 7.

**Figure 7.** Specific heat for steel at elevated temperatures. BS EN 1993.

The thermal conductivity of steel is 53.3 W/m°C when the temperature is 20°C and it rises to 27.4 W/m°C when the temperature is 800°C. However, the thermal conductivity is stable when the temperature is over 800°C. The density of steel is 7850 kg/m3. Rosanne et al. [12] performed research on the thermal performance of a series of insulation materials. According to their related data, the specific heat of calcium silicate board is 819.4J/kg°C. The regulation of GB/T 10699—1998[13] stipulates the thermal conductivities of calcium silicate board at various temperatures and other parameters. Its thermal conductivity as follow.

\[
\lambda = \begin{cases} 
0.0564+7.785 \times 10^{-5} \times t+7.8571 \times 10^{-3} \times t^2 & (t \leq 500°C) \\
0.0937+1.67397 \times 10^{-10} \times t^3 & (500 < t \leq 800°C) \\
0.179 & (t > 800°C)
\end{cases}
\]  

where

- \(\lambda\): Thermal conductivity (W/m°C)
- \(t\): temperature (°C)

In the research made by Nassif et al. [14], it presents some material property parameters related to rock wool. Combining the specifications of rock wool used in this research, the final specific heat, thermal conductivity and density of rock wool are respectively 840 J/kg°C, 0.035 W/m°C and 60 kg/m³. The specific setting is shown as Table 1.
Table 1. Thermal properties.

| Material    | Specific heat (J/kg\(\degree\)C) | Thermal conductivity (W/m\(\degree\)C) | Density (kg/m\(^3\)) |
|-------------|-----------------------------------|----------------------------------------|-----------------------|
| Steel       | According to Fig. 7               | 20\(^\circ\)C, 53.3 T\(\geq\)800\(^\circ\)C, 27.4 | 7850                  |
| Calcium Silicate | 819.4                           | According to (2)                     | 1350                  |
| Mineral Wool | 840                              | 0.035                                  | 60                    |

4. Results and discussion

4.1. Experiment results

The test time lasts 60 minutes. After 9 minutes of the test, trace smokes with abnormal taste burst out above the unexposed surface of specimen and the seams of framework. At this time, all temperatures of measuring points obviously tend to rise. Until 14\(^{th}\) minute, the temperature of measuring point on unexposed surface tends to decline until the 35\(^{th}\) minute. From the 35\(^{th}\) minute to the end, the temperatures rise all the time. The temperature inner wall fire part rises rapidly after 9 minutes and it slowly rises to the end after 22 minutes. At the end of test time, the temperature of measuring point is 738.1\(^\circ\)C. The temperature inner wall middle part rises rapidly after the test begins 9 minutes and it begins to slowly rise to the end after 38 minutes. At the end of test time, the temperature of measuring point is 487.8\(^\circ\)C. The situation of temperature inner wall cold part is generally the same to the temperature side wall within the first 18 minutes. After that, the temperature gradually goes up to the end and the final temperature is 316.5\(^\circ\)C (see figure 8). At 21\(^{st}\) minute, a transverse crack appears on the upward side of left board of unexposed surface and the crack extends to the center at 38\(^{th}\) minute. When the test time is over, the temperature upper left center is the highest one among temperatures on unexposed surfaces, is 104.7\(^\circ\)C and the highest average temperature is 97.5\(^\circ\)C (see figure 9) which is not in excess of stipulated fire resistance in regulations of ISO 834-1[2]. After the test, the integrity of unexposed surface of specimen is still good (see figure 10). Therefore, the specimen meets the demand of 60 minutes fire resistance.

![Figure 8. Measure temperatures compared to simulation values.](image-url)
4.2. Comprehensive discussion
Although the test boards have some cracks on the surface facing the fire during the experiment, the surface does not explode, and the integrity is good by visual inspection. After testing it for 60 minutes, the fire resistance meets the requirements of ISO 834-1 [2] and the 60 min of fire ratings. From the 14th to the 35th minute, the temperature shows a steady decrease, indicating that there is some moisture inside the board and the rock wool to absorb the heat. The temperature at the surface on the backside then starts going up only after the material itself is totally dried. This often occurs in firewall tests when the material is more consistent. For example, the metal sandwich wall shows such phenomenon. The metal surface does not get burned, and the insulation layer (rock wool) in between can consistently absorb heat for a while. Only when the heat reaches saturation will the temperature on the surface not facing the fire continue to go up.

The full-scale standard test specimen and the CFD finite element numerical modelling have the same location of measuring points. The results by comparing numerical modelling and standard fire test is shown as figure (see Figure 8). The heating curve of test furnace is responding to the modelling standard heating curve, shows that the standard fire test temperature conforms to the regulation of ISO 834-1[2]. In the standard fire test, the temperature inner wall fire part rises faster in the first 22 minutes of test and rises slower from 22nd minutes to 60th minutes. Similarly, although the heating curve of numerical modelling on this measuring point is relatively ideal, it can be found that the escalating trend of temperature in first 20 minutes is obviously higher than that in last 40 minutes, basically coincident with the escalating trend of this measuring point in standard fire test. In first 20 minutes, the temperature inner wall middle part rises slower, and after that it rises faster. At 21th minutes, a transverse crack appears on the upward side of left board of unexposed surface, so that
causes that the temperature rises faster. Because the numerical modelling is in an ideal condition, the numerical modelling temperature on this point rises slowly all the time, and the situation that its temperature slope and temperature slope of standard fire test alternate with each other may occur. However, the overall escalating trends are highly coincident. The temperature inner wall cold part is away from the fire source, so its temperature heating curve is gentler than previous two temperatures and it is highly correlated to the numerical modelling temperature. In standard fire test, trace smokes with abnormal taste burst out above the unexposed surface of specimen and the seams of framework at 9th minute, so the average temperature on unexposed surface greatly rises but tends to rise slower, corresponding with the numerical modelling temperature. Through the comparison, it can be found that the temperature ascending curves of different measuring points of numerically predicted values are highly correlated to the data of all temperature measuring points in standard fire test in 60 minutes.

5. Conclusion
This is an innovative research. It successfully builds the CFD numerical models which is corresponding with the specimens, successfully predicts the effect of reinforcement by modified model parameters and verifies it in the following standard fire test. It’s proved that the numerical modelling corresponding with the standard fire test is effective. Similar patterns can be applied to other researches on the wall systems and that can greatly save the cost of test. Before the test, the numerical modelling can be processed to work out the predicted results.

6. References
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