FURNACE TESTING OF FULL-SCALE GYPSUM STEEL STUD NON-LOAD BEARING WALL ASSEMBLIES: RESULTS OF MULTI-LABORATORY TESTING IN CANADA, JAPAN, AND USA

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ABSTRACT

The present paper discusses the results of a multiple laboratory test program aimed at determining the consistency of large scale furnace testing. The North American Fire Testing Laboratories Consortium (NAFTL) organized a multiple laboratory test program for ASTM E119-00 using a common structural element: a 1-h rated gypsum/steel-stud non-load bearing wall assembly. Walls were tested by six different organizations employing ten different furnace facilities following the guidance provided in ASTM E119-00. In addition to NAFTL members conducting the tests, the program was expanded to include four testing laboratories in Japan; the Center for Better Living served as the organizer for the Japanese testing. Results obtained from these experiments are discussed.

1. INTRODUCTION

Traditional fire resistance testing in the United States has been based upon ASTM standard E119, "Standard Test Methods for Fire Tests of Building Construction and Materials"[1]. The similar international standard is ISO 834[2]. In these tests, building components are subjected to a constantly increasing furnace temperature intended to represent a standard fire. The components are then rated, with units of time, on their ability to withstand the exposure up to a criterion that is defined as a failure point. This criterion may be either based on the temperature rise of the unexposed face of the partition assembly or the efflux of hot gases or flames. It is expected that a 2-h rated wall would resist failure in a real fire for a longer period of time than a similarly functioning 1-h rated wall, and this is invariably the case. What can not be expected, however, is that a 2-h rated wall would

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necessarily withstand an actual fire in a building for two hours, or that the wall would necessarily fail after two hours. The inability of the fire resistance rating to act as an absolute predictor of performance in an actual fire was recognized from the beginning when the forerunner of ASTM E119 was published in 1918. The reference to fire resistance ratings in common time units has become erroneously interpreted to relate closely (or at least conservatively) to the actual time that a wall would be expected to resist a fire.

Clearly, there are additional limitations to this approach in providing a known degree of fire safety. The test is concluded when the first failure criterion is met. For wall, floors, and ceiling assemblies, this is almost always an excessive temperature on the unexposed face. The more serious fire hazard is the passage of smoke and flames through the partition, and the time to this failure is rarely measured. In addition, there is no method available to relate the response of the partition under this standard exposure to its response in a different (more realistic) design fire. Most realistic fires do not heat a partition uniformly[3]. Real fires can recede, allowing the partition to cool while still in the presence of smoke and flames. In spite of severe shortcomings, these test methods continue to be used throughout the world because (i) a massive data base has been established and is in continual use, (ii) history suggests that the test methods are conservative, and (iii) alternative methods have not been developed yet that are acceptable to the major parties involved.

In any event, designing structures to withstand the hazard posed by an unconfined building fire requires that current (and future) standard fire resistance tests be reliable and consistent, independent of the laboratory performing the test. To this end, the North American Fire Testing Laboratories (NAFTL) consortium was formed in 2004 to provide a forum for the exchange of technical information, to conduct studies, and to develop industry consensus positions relating to the full range of fire tests. Current members include Southwest Research Institute (SwRI), Underwriters Laboratories (UL), FM Approvals, Intertek, NGC Testing, and Western Fire Center. The National Institute of Standards and Technology (NIST), the National Research Council of Canada (NRC-C), and the Fire Testing Laboratory of the Bureau of Alcohol, Tobacco, and Firearms (ATF) are non-voting associate members of NAFTL. The organization is open to any North American-based independent commercial laboratory engaged in fire testing or research.

As a means to overcome the shortcomings previously enumerated, NAFTL organized a multiple laboratory test program for ASTM E119-00[1] using a common structural element: a 1-h rated gypsum/steel-stud non-load bearing wall assembly. Walls were tested by six different organizations employing ten different furnace facilities following the guidance provided in ASTM E119-00[1]. In addition to NAFTL members conducting the tests, the program was expanded to include four testing laboratories in Japan; the Center for Better Living served as the organizer for the Japanese testing. The collaboration between NIST and the Center for Better Living is part of an international effort to assess the performance and failure mechanisms of gypsum wall assemblies under real fires/furnace conditions and to collect data that are necessary to validate models that could be used to predict their performance and ultimate failure under various design fires.

NIST was the qualified independent party responsible for analyzing and reporting the data for the NAFTL and Japanese Laboratory testing[4]. The present study expands on a recently released NIST internal report[4] to include further characterization of the gypsum board used in the tests, reporting the findings of the multiple laboratory testing program using the International System of units (SI), and comparing probes used to characterize furnace temperatures.

2. WALL ASSEMBLY CONSTRUCTED FOR TESTING

A non-load bearing wall consisting of gypsum panels attached to steel studs was constructed for fire testing. Figure 1 displays a detailed drawing of the assembly construction. Steel studs (width: 92 mm, thickness: 25 gauge) were spaced at 406 mm, and type X gypsum panels (USG[i]) with a thickness of 15.9 mm were attached vertically to the studs using type S drywall screws spaced at 305 mm. All of the gypsum board used in this study was provided by USG from a single production run to ensure uniformity. The seams were staggered on the exposed and unexposed face. The partitions were constructed under ASTM guidelines for non-load bearing wall assemblies[5-8]. Following ASTM-E119-00[1], temperatures of the unexposed face were measured using thermocouples placed under insulating pads. In addition to this, temperatures were measured inside the cavity of the constructed assemblies. The location of the temperature measurements are shown in Figure 1.

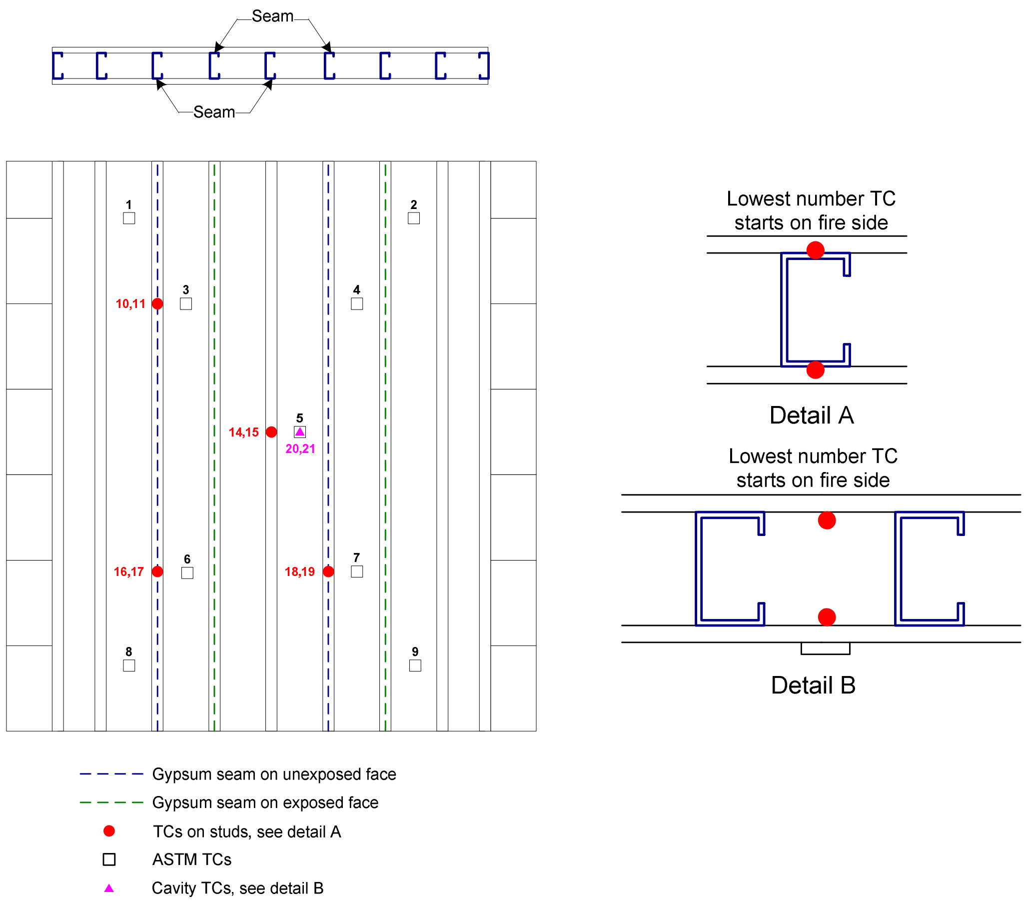


Fig. 1 Drawing of assembly used for testing by all laboratories

[i] Certain commercial products are identified to adequately describe the experimental procedure; this in no way implies endorsement from NIST.

3. GYSPUM BOARD THERMAL PROPERTY CHARACTERIZATION

The thermal properties of the gypsum board used for these experiments were characterized. Thermal properties are required to model the performance of gypsum assemblies used as part of this test series. In addition to this, it was desired to compare the properties of the gypsum board provided for this test series to those of off-the-shelf Type X gypsum board (15.9 mm). The thermal conductivity and specific heat were determined as a function of temperature for representative gypsum board samples. The thermal conductivity as a function of temperature was determined using the Slug Calorimeter[9]. The slug calorimeter is comprised of a square central stainless steel plate (152 mm by 152 mm by 12.7 mm). A set of 152 mm by 152 mm gypsum board samples (with paper carefully removed) was installed in a 'sandwich' configuration (i.e. steel slug in the center); this provided an adiabatic boundary condition at the central axis of the slug plate. This entire configuration was then placed at the bottom of an electrically heated box furnace and the temperatures of the metal slug and exterior gypsum board surfaces were recorded during multiple heating and cooling cycles. The effective thermal conductivity was estimated knowing the heat capacities and densities of the steel slug and gypsum board samples (determined for the gypsum board using the Hot Disk Thermal Constants Analyzer)[4,9].

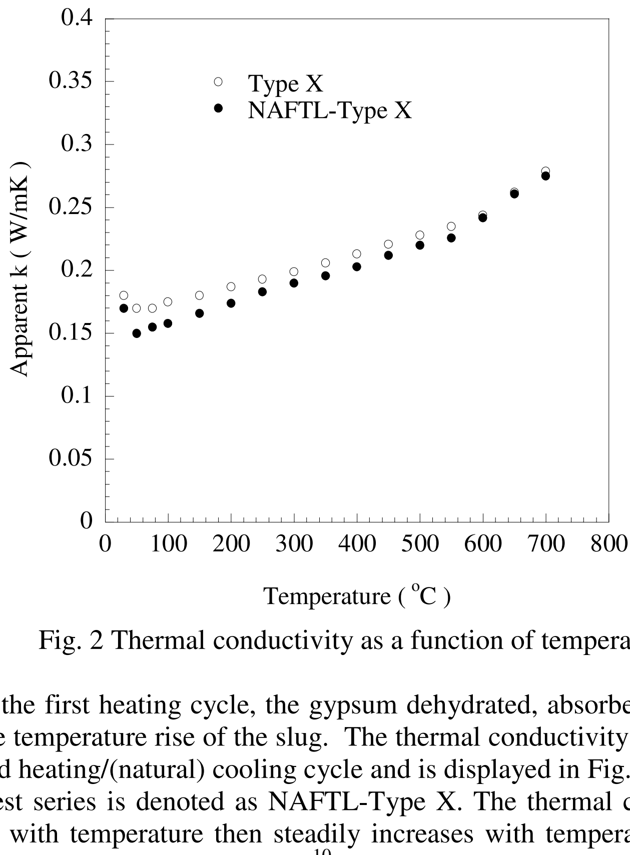
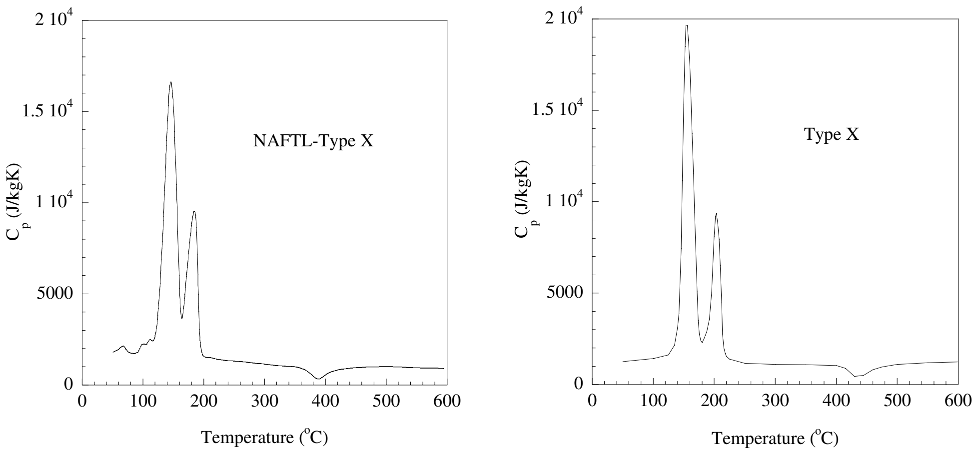


Fig. 2 Thermal conductivity as a function of temperature

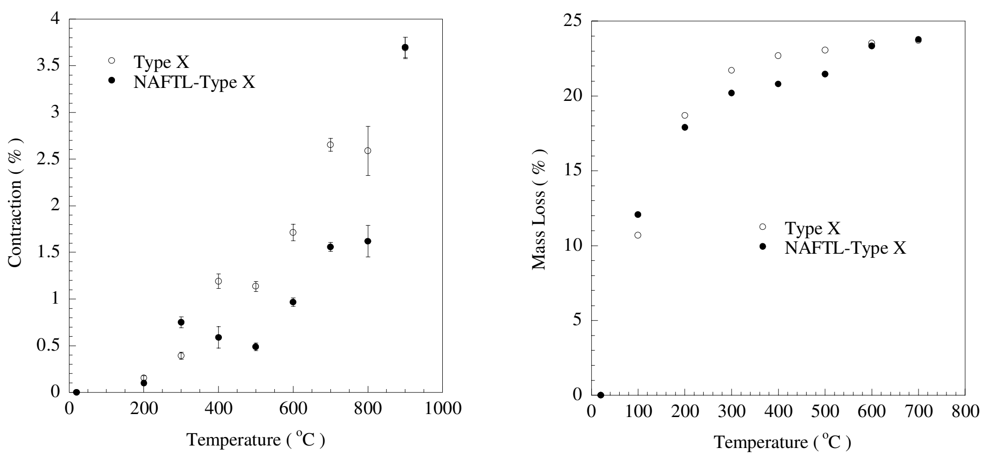
During the first heating cycle, the gypsum dehydrated, absorbed some of the energy, and delayed the temperature rise of the slug. The thermal conductivity was determined based upon the second heating/(natural) cooling cycle and is displayed in Fig. 2. The gypsum board used for this test series is denoted as NAFTL-Type X. The thermal conductivity exhibits a slight decrease with temperature then steadily increases with temperature; similar behavior has been observed by Bénichou and Sultan[10] for thermal conductivity measurements for other gypsum board types. The NAFTL-Type X gypsum board used as part of the test series resulted in a slightly lower thermal conductivity as compared to off-the-shelf Type X gypsum board up to temperature of 500 °C. Above these temperatures, little difference was observed between the two gypsum samples.

To determine the specific heat as a function of temperature, Differential Scanning Calorimetry (DSC) was used. DSC specific heat measurements were taken following the procedure outlined in ASTM E 1269-2001[11] at a scanning rate of 20 °C/min. The gypsum board samples used were 10 mg in initial mass. To accommodate the gas generation incurred from dehydration, the sample, reference and standard measurements utilized pans that were sealed except for a 50 µm pinhole in the lid. Figure 3a-b displays the results of these measurements for the NAFTL-Type X board and off-the-shelf Type X board. As can be seen, three reactions are observed for both gypsum board types. Details of these reactions have been described elsewhere[3]. Slight differences were observed in the magnitude of the specific heat for the first dehydration reaction; these differences are within the uncertainty of the measurement.



(a) (b)

Fig. 3 (a) Specific heat as a function of temperature for NAFTL-Type X gypsum board (b) Specific heat as a function of temperature for off the shelf Type X board



(a) (b)

Figure 4 (a) Gypsum board contraction as a function of temperature (b) Gypsum board mass loss as a function of temperature; each data point is the average of three repeat measurements

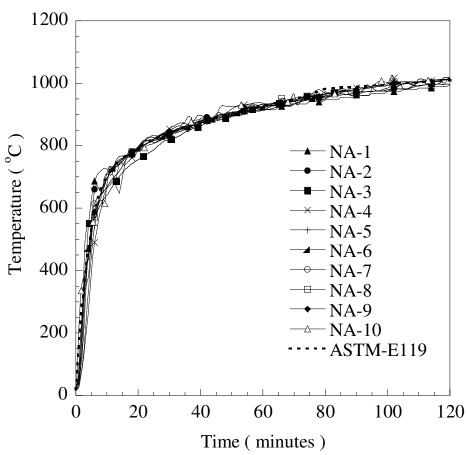
The mass loss and linear contraction were measured for the NAFTL-Type X gypsum board and off-the-shelf Type X gypsum board. Samples were cut into 50 mm by 152 mm rectangles from single sheets of each type of board and inserted into an oven. At each temperature tested, the mass loss was measured as function of time. For a given temperature, the gypsum board samples were inserted into an oven for up to 24 hours. For each temperature tested, no change is mass loss or contraction was observed after the samples were allowed to equilibrate in the oven after three hours of heating. The results of these measurements are displayed in Fig. 4a-b. The contraction of the NAFTL-Type X gypsum board was considerably less at higher temperatures compared to off-the-shelf gypsum board.

Finally, the density at room temperature was determined from 152 mm by 152 mm samples. Based on these measurements, the density was higher for NAFTL-Type X board (760 kg/m^3 ± 0.01 kg/m^3; mean ± standard deviation) as compared to off-the-shelf Type X board (711 kg/m^3 ± 0.02 kg/m^3; mean ± standard deviation).

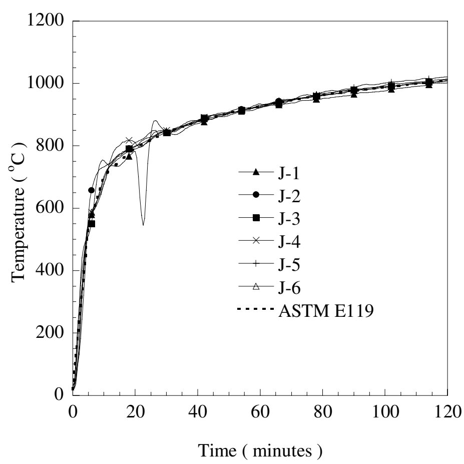
In summary, the linear contraction as well as the density was higher for the NAFTL Type-X gypsum board as compared to off-the-shelf Type X gypsum board. These results suggest a higher content of additives were present in the NAFTL Type-X gypsum board. Core additives are known to be added to enhance gypsum board performance.

4. FULL-SCALE TEST RESULTS

According to ASTM E119-00[1] specifications, the temperature of the furnace is determined from the average of multiple shielded, slow time-response thermocouples located within the furnace cavity. Each laboratory that participated in the testing mounted the test assembly in their vertical furnace. The temperatures of the North American laboratory furnace tests, designated NA-1 through NA-10, are plotted in Fig. 5a. The temperatures of the Japanese laboratory furnace tests, designated J-1 through J-6, are plotted in Fig. 5b. The dotted line represents the time-temperature curve specified in the ASTM E119-00[1] standard. As can be seen, furnace J-1 failed at approximately 20 minutes into the test. The furnace was subsequently brought on-line again within three minutes of the failure; the cause of failure was due to the activation of a seismic sensor.



(a)



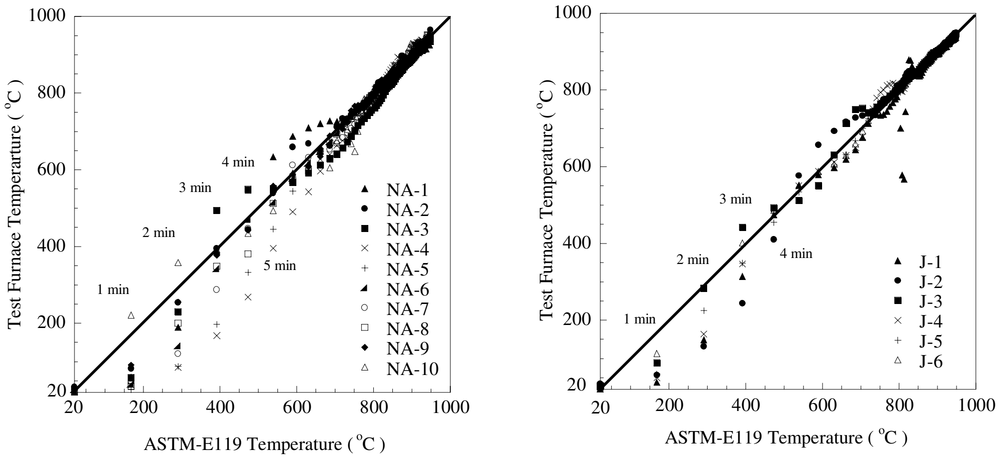
(b)

Fig. 5 (a) Furnace temperature for North American Laboratories (b) Furnace temperature for Japanese Laboratories

Fig. 6a-b displays how closely the furnace temperatures follow the standard temperature curve. One can see that during warm-up, the test furnaces in North America and

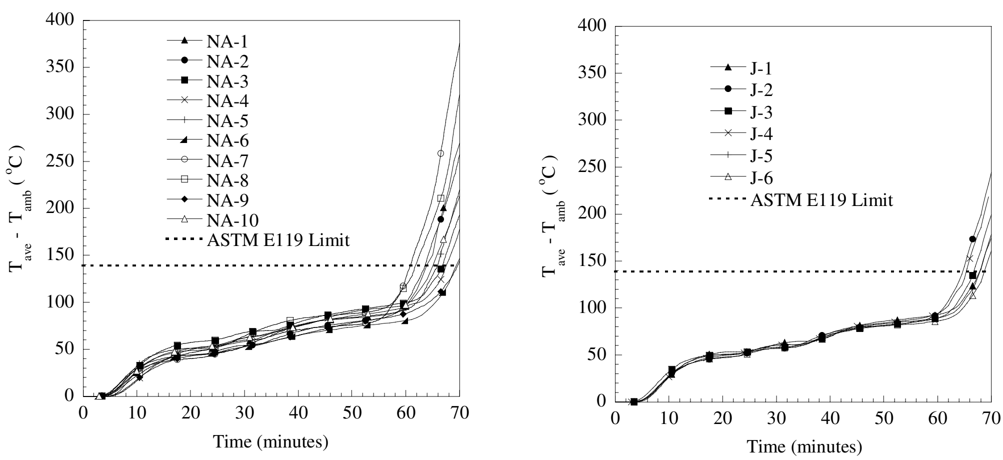
Japan deviate by as much as 150 °C from the ASTM E119-00[1] temperature, and are most often on the low side. Due to failure of furnace J-1, a large discrepancy was observed between the E119-00 temperature and furnace J-1.

The average temperature increase on the unexposed wall for each North American and Japanese furnace test is shown in Fig. 7a-b. Note that the ambient temperature has been subtracted from the average temperatures. As mentioned earlier, one of the criteria for rating the fire resistance of a wall assembly is the time when the average temperature of the thermocouples on the unexposed side of the specimen reaches 139 °C above its initial average temperature. This limit is shown as the dotted red line in the figures. Similar to the North American furnaces, the temperature profiles are closely grouped for the first 60 minutes and then begin to diverge. None of the average temperature increases exceed the threshold before 60 minutes, and all have exceeded the threshold by 70 minutes.



(a) (b)

Fig. 6 (a) Individual furnace temperatures vs. prescribed furnace temperatures-North American Laboratories (b) Individual furnace temperatures vs. prescribed furnace temperatures-Japanese Laboratories



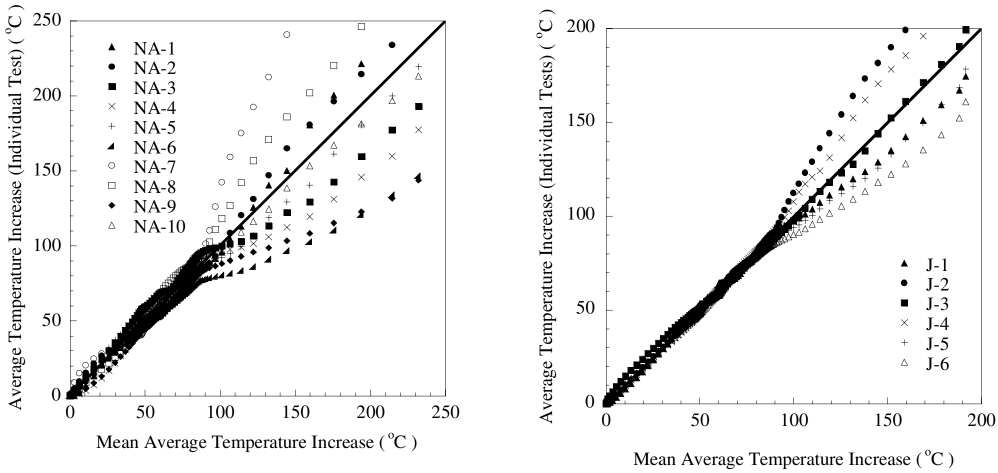
(a) (b)

Fig. 7 (a) Average unexposed face temperatures-North American Laboratories (b) Average unexposed face temperatures-Japanese Laboratories

Furnace pressures were recorded for the North American Laboratories and the Japanese Laboratories. These data are presented elsewhere[4]. A complication with this data was that the location of pressure probe was not the same between each test. As a result, comparing the furnace pressure among laboratories was not useful.

Fig. 8a-b is a plot of the average temperature increase on the unexposed wall for the individual specimen versus the mean value for the temperature increase of all of the tests. The spread in temperatures among the six Japanese Laboratories begins at around 77 ^{o}C, which was very similar to the North American tests. Above these temperatures, the deviation among furnaces is quite large; more than 93 ^{o}C at later times for both the North American and Japanese Laboratories.

The key finding of the ASTM E119-00[1] is the fire resistance rating (see Table 1 and Table 2). For one of the Japanese furnaces, the failure time was based upon the average temperature increase on the unexposed face exceeding 139 ^{o}C. The maximum allowed individual temperature on the backside of the wall (181 ^{o}C) was the failure limit for four Japanese furnaces; one furnace exceeded both criteria simultaneously (within the limit of their data rate). In no case was the wall breached in less than 70 minutes. The wall was not designed to be loaded; hence, the failure to maintain a load was not examined.



(a) (b)

Fig. 8 (a) Individual test unexposed surface average vs. mean of all ten tests-North American Laboratories (b) Individual test unexposed surface average vs. mean of all six tests-Japanese Laboratories

For five of the North American furnaces, the failure time was based upon the average temperature increase on the unexposed face exceeding 139 ^{o}C. The maximum allowed individual temperature on the backside of the wall (181 ^{o}C) was the failure limit for four North American furnaces, and one North American furnace exceeded both criteria simultaneously (within the limit of their data rate).

In summary, for the Japanese furnaces the overall average time to failure was 67.1 minutes, with a standard deviation of 1.1 minutes. For comparison (see Table 1 and Table 2), the North American furnaces resulted in an overall average time to failure was 65.0 minutes, with a standard deviation of 2.8 minutes. Similar to the North American furnace tests, the fire resistance rating, shown in the second column, is the same for all six Japanese furnaces: 1-h.

4.1 COMPARISON OF FURNACE THERMOCOUPLES

Differences exist between ASTM E119-00[1], ISO 834[2], and Japanese protocols for fire resistance testing of partition assemblies; the measuring probe for monitoring and controlling the furnace temperature is one difference. While both ASTM E119-00[1] and Japanese testing protocol continue to use thermocouples to control the furnace temperature, the ISO 834[2] testing protocol was modified to use the plate thermometer.

Table 1 Summary of Failure Criteria for Japanese Laboratories; all of the Japanese Laboratories arrived at the same Fire Resistance Rating

Laboratory	Fire Resistance Rating	Time to First Failure, minutes	Failed Thermocouple Reading	Other TC's Failing within 1 minute
NA-1	1 hour	64	average	TC3, 5, 7
NA-2	1 hour	62.8	TC3	average
NA-3	1 hour	66.8	average	TC4, 6, 8
NA-4	1 hour	67.5	average	TC3, 6, 8
NA-5	1 hour	65.8	average	TC6
NA-6	1 hour	70	TC3	TC4, 5, 6, 7, average
NA-7	1 hour	60.6	TC7	TC3, 5, 6, average
NA-8	1 hour	61.9	average	TC3, 4, 6
NA-9	1 hour	65.8	TC5	none
NA-10	1 hour	65	average, TC5	TC4, 6, 7
average	1 hour	65.0 +/- 2.8	average	--

Table 2 Summary of Failure Criteria for North American Laboratories

Laboratory	Fire Resistance Rating	Time to First Failure, minutes	Failed Thermocouple Reading	Other TC's Failing within 1 minute
J-1	1 hour	67.7	TC7	Ave., TC6
J-2	1 hour	67.3	TC7	Ave., TC6
J-3	1 hour	66.0	TC6	Ave.
J-4	1 hour	65.5	Ave.	TC3, TC4, TC5, TC6, TC7
J-5	1 hour	68.0	Ave., TC6	TC4, TC5, TC7
J-6	1 hour	68.0	TC7	Ave.
average	1 hour	67.1 ± 1.1	TC7, TC6, Ave	--

For consistency, as part of the full scale testing, all laboratories (NA-1 through NA-10; J-1 through J-6) followed the ASTM E119-00[1] testing method; ASTM thermocouples were selected to control the furnace temperature. For comparison purposes, some of the Japanese laboratories decided to insert all three measuring probes inside the furnace to monitor the furnace temperature. These results obtained from this exercise are displayed in Fig. 9. At the inception of the test, the ASTM thermocouples lagged behind the ASTM-E119-00[1] time-temperature curve. After 10 minutes, there was essentially no difference between the three furnace probes designs. Similar results have been presented by Sultan for a comparison of ASTM shield thermocouples to plate thermometers[12]. For gypsum board partition assemblies, such differences may not be important. However, for assemblies constructed of other materials, such variations may be important. This subject, however, is beyond the scope of the present study.

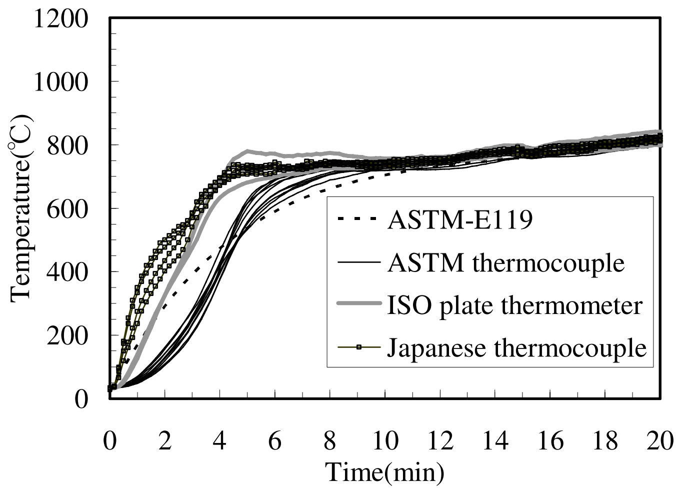


Fig. 9 Furnace temperature recorded by ASTM thermocouples, ISO plate thermometer, and Japanese thermocouples. Japanese bare-bead thermocouple with open protection tube, ISO plate thermometer, and ASTM thermocouple with closed protection tube

5. CONCLUSIONS

The North American Fire Testing Laboratories Consortium (NAFTL) organized a multiple laboratory test program for ASTM E119-00 using a common structural element: a 1-h rated gypsum/steel-stud non-load bearing wall assembly. Walls were tested by six different organizations employing ten different furnace facilities following the guidance provided in ASTM E119-00. In addition to NAFTL members conducting the tests, the program was expanded to include four testing laboratories in Japan; the Center for Better Living served as the organizer for the Japanese testing. NIST was the qualified independent party responsible for analyzing and reporting the data for the NAFTL and Japanese Laboratory testing. The present study expanded on a recently released NIST internal report to include further characterization of the gypsum board used in the tests as well as reporting the findings of the multiple laboratory testing program using the International System of units (SI).

The thermal properties of the gypsum board used for these experiments were characterized and compared to off-the-shelf Type X gypsum board. It was observed that the thermal conductivity and specific heat was not significantly different between the NAFTL-

Type X gypsum board and off-the-shelf Type X gypsum board. The linear contraction as well as the density was higher for the NAFTL-Type X gypsum board as compared to off-the-shelf Type X gypsum board. These results suggest a higher content of additives were present in the NAFTL Type-X gypsum board.

With regard to the full scale assembly tests, for five of the North American furnaces, the failure time was based upon the average temperature increase on the unexposed face exceeding 139 ^{o}C. The maximum allowed individual temperature on the backside of the wall (181 ^{o}C) was the failure limit for four North American furnaces, and one North American furnace exceeded both criteria simultaneously (within the limit of their data rate).

For the Japanese furnaces the overall average time to failure was 67.1 minutes, with a standard deviation of 1.1 minutes. For comparison, the North American furnaces resulted in an overall average time to failure was 65.0 minutes, with a standard deviation of 2.8 minutes. Similar to the North American furnace tests, the fire resistance rating was the same for all six Japanese furnaces: 1-h. The effort described in this paper was the largest ever conducted for fire resistance testing. A similar effort is now underway for load-bearing partition assemblies.

6. AKNOWLEDGEMENTS

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