MECHANICAL PROPERTIES OF GYPSUM BOARD AT ELEVATED TEMPERATURES

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ABSTRACT

Gypsum board is a common fire barrier used in house and general building construction. Recently, evaluation of the collapses of the World Trade Center Towers highlighted the potential role and failure of gypsum board in containing the fires and resisting damage. The use of gypsum board as primary fire protection of light-flame wood or steel construction is ubiquitous. Yet knowledge of the common engineering mechanical properties of this construction product is nearly nonexistent. Gypsum board is used in a prescriptive manner with little or no rational design. Summarized here are the results of a study examining the mechanical properties of Type X gypsum board at elevated temperatures. These properties are needed to contemplate the engineering design of gypsum board fire barriers. Tests were undertaken with a small oven within a test machine measuring mass loss, shrinkage, bending strength and modulus of elasticity at elevated temperatures to 400°C. The research showsthat shrinkage and calcination of the gypsum board appear complete between 20 to 30 minutes of exposure at a uniform 400°C. Only after complete calcination, where all moisture is driven off, does the bending strength approach 0. Strength appeared to decrease linearly with increasing temperature. Mass loss and modulus of elasticity exhibited similar trends with the greatest decreases occurring from 100°C to 200°C followed by more gradual decrease to 400°C. The surface paper plays significant stiffening and strengthening roles up to 60 minutes at temperatures as high as 200°C.

INTRODUCTION

Gypsum board partitions and ceiling membranes are perhaps the most common fire resistant construction strategy employed in a wide variety of building types. Very common in light frame construction associated with single and multi-family housing, gypsum board partitions are also used in other larger building types. The fire resistance of the World Trade Center buildings brought new attention to the current approaches to designing fire resistance in the United States and has highlighted the role played by gypsum board. At the stairs and elevator shafts, fire separation partitions consisted of steel stud and gypsum board assemblies where the gypsum board became detached during the destruction.

Typically construction of gypsum board partitions and ceiling are prescribed by the building code or are specified by the architect to achieve a fire rating for a given construction type. The performance characteristics of a given gypsum board design as selected by the architect has been predetermined from results of the ASTM E-119 test. This test lumps together the structural performance and fire performance of the membrane into one simple performance measure. Unlike many other aspects of the building, the structural engineer has no role in designing or specifying the gypsum board. Yet, the gypsum board frequently is a structural element in the design, providing lateral support to structural members and in wood design providing a basis for repetitive member increase. So if the gypsum board plays a role both in structural performance and fire protection performance of an assembly, then could its performance be optimized by explicitly considering its performance as part of the design of a structural assembly?

The major challenge in contemplating this question is that the engineering properties of gypsum are largely unknown at both normal temperatures and those associated with a fire. Generally, thermal data for gypsum board are available but engineering property data at ambient and elevated temperatures are rare as indicated in the *SFPE Handbook of Fire Protection Engineering*[1]. A limited amount of engineering data for gypsum board has been previously published[2,3,4]. By engineering properties we mean properties such as modulus of elasticity and bending strength. Fuller reported bending strength and modulus of elasticity for 13-mm gypsum board at temperatures ranging from 50°C to 140°C[3]. Clancy reports of several investigations conducted in Australia where properties were measured primarily at room temperature (ambient)[4]. Ambient tensile strengths were in the range of 1.0 to 2.0 MPa and ambient modulus of elasticity values were in the range of 1.0 to 2.0 GPa for the Australian studies reported[4]. It was noted the stress-strain curve was highly nonlinear in tension and that the panel was stronger along its length as compared to along its width. This was attributed to a biased orientation of the glass reinforcing fibers. The Australians reported only 10% of the tensile strength remained at 320°C but lower temperatures toward ambient were not considered. Other studies by Hamathy[5,6] Lawson[7] and Mehaffey[8] have revealed many of the thermal properties of different gypsum boards, but not the mechanical properties.

Gypsum board consists of calcium sulfate in the form of dihydrate crystals with paper on either side. Different additives may be included to improve the fire resistance of the board, such as glass fibers or vermiculite. In the United States, Type X board is a fire-rated board containing glass fibers, and potentially other additives. Type X board is defined based only on performance as a sheathing that will provide a 60-minute load-bearing fire resistance when one 15.9 mm board is attached to each side of a wood or steel stud wall assembly[9]. Gypsum board undergoes calcination when exposed to temperatures above 100°C. Chemically combined water is expelled by the gypsum board between 100°C and 125°C, reducing the gypsum to plaster of paris as shown chemically in Eq. 1[4].

$$CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 \cdot \tfrac{1}{2}H_2O + 1\tfrac{1}{2}H_2O \qquad [1]$$

There is no information available on the rate at which this reaction occurs. With fire exposed to one side of the board, the calcination process proceeds gradually through the board thickness consuming thermal energy and limiting temperatures on the backside of the board to about 120°C. Board density and initial moisture content are important factors that influence the fire. resistant capabilities of the gypsum board. Different investigators report different temperatures and times necessary to achieve complete calcination (and thus loss of strength) suggesting a temperature dependency for the rate of reaction. The glass fibers and vermiculite in Type X gypsum board help retard shrinkage and the associated formation of cracks.

RESEARCH APPROACH

Gypsum board is not an isolated and independent component in the fire resistance of a structure. Gypsum board performance depends both on the stresses accumulated during loading and heating of the assembly. There will be an interaction between response of the assembly and the stresses in the gypsum. Gypsum stresses in a ceiling assembly will develop primarily from three sources as indicated in Eq. 2.

$$\sigma_{gypsum} = \sigma_{bending} + \sigma_{screwtransfer} + \sigma_{shrinkage} \quad [2]$$

where σ_{gypsum} is the overall normal stress in the gypsum resulting from $\sigma_{bending}$,the bending stress generated by bending from self weight and bending imposed by compatibility with the displacements of the supporting members, $\sigma_{screw\ trasnfer}$, stresses resulting from the transfer of forces from the wood members through the screws or other attachment scheme, and $\sigma_{shrinkage}$, stresses resulting from the restraint caused by the screws or other attachment scheme to the shrinkage of the gypsum board. Failure of gypsum board will occur when internal stresses equal the residual strength.

$$\sigma_{gypsum} = Strength_{gypsum} \quad [3]$$

To conduct an analysis as characterized by Eqs. 2 and 3, research has been completed to measure the modulus of elasticity and bending strength of gypsum board. All tests were conducted on one lot of 15.9-mm thick Type X gypsum board. Tests reported herein are a) dimensional and mass change, b) modulus of elasticity and c) bending strength. Properties were measured on specimens mounted within a convection-heated test chamber and loaded with a screw-driven test machine. Properties were measured at 23°C, 100°C, 200°C, 300°C and 400°C. A high temperature linear differential induction transducer was used to measure displacements and dimensional changes of the specimen within the oven. Load tests were conducted at elevated temperatures after soak times of 15 minutes and 60 minutes at the target temperature with no load applied. A total of nine tests were conducted for each condition with at least 4 specimens obtained from cuts along the length of the panel and at least 4 specimens cut from the width of the panel corresponding to the machine direction of the face paper and the cross direction respectively. These specimens were cut from a minimum of 3 different panels. The specimens were conditioned at 23°C and 50% relative humidity for at least 30 hours prior to testing as it was determined that initial moisture content based on the surrounding relative humidity caused a significant influence in measured material response.

The test setup was configured to provide repeatable measures of material properties at different temperature exposures and not to precisely replicate conditions during a fire. At least two significant differences between test conditions and fire conditions are acknowledged to exist. First, in these tests both sides of the gypsum board specimen were exposed to the same elevated temperature unlike the single-sided exposure in an assembly test. Second, test temperatures were limited to 400°C even though much higher temperatures will likely occur in a fire to the exposed side of the gypsum. Applications of these research results must consider these factors. Other limitations are that gypsum board products can vary significantly from manufacturer to manufacturer. In addition, the brittle nature of the gypsum core combined with the ductile nature of the bonded paper results in a composite product of considerable complexity.

Intermediate-scale assembly tests have also been conducted and at this writing are still in-progress. These assemblies consist of three 2-by-4 wood members with the 15.9-mm gypsum board attached to the underside and subject to bending and tension loads.

GYPSUM BOARD MATERIAL TEST RESULTS

Temperatures were monitored at the center of the gypsum board to gain an understanding of the rate of temperature rise through the gypsum board. Figure 3 summarizes the most important characteristics observed. First, the mid-depth temperature exceeded the exposure temperature in tests subjecting gypsum board specimens to constant 300°C and 400°C. The cause of this phenomenon has not been previously reported and remains under investigation. Second, the rate of mid-depth temperature rise in the small-scale material tests at constant 400°C was approximately equal to the mid-depth temperature rise of the gypsum board in an E-119 type exposure. This facilitates the application of the small scale test results to more practical fire test conditions.

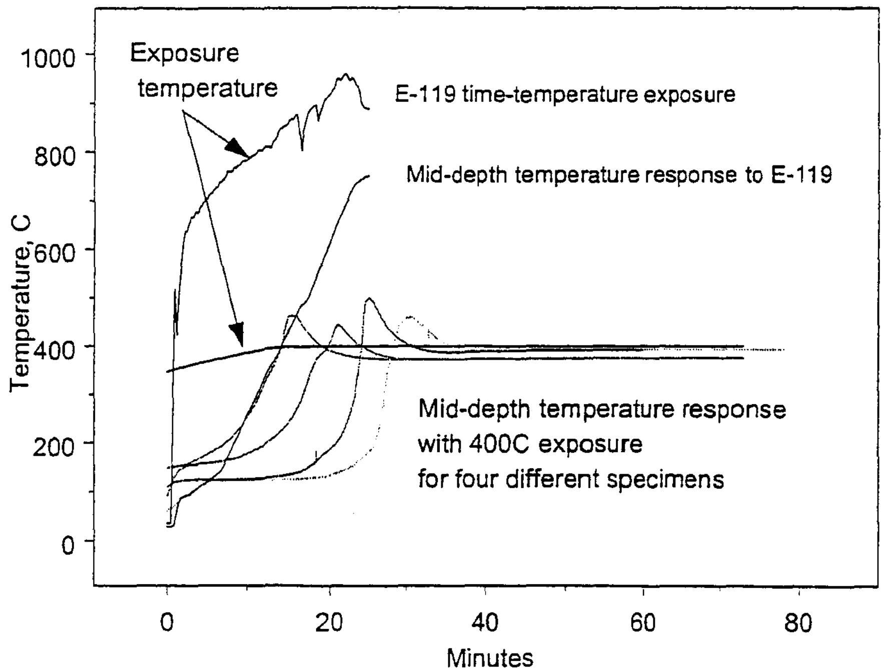

Figure 1. Temperature Rise at Mid-depth in Gypsum Board

Shrinkage specimens were 203-mm by 51 -mm and were heated without restraint for up to 60 minutes at the specified target temperature (100°C, 200°C, 300°C and 400°C). As suggested by the data in Fig. 1, prior to 60 minutes of heating the gypsum had reached a thermal equilibrium for all temperature conditions. The results were consistent with that observed by other investigators such as Harmathy[4]. A typical shrinkage versus time plot is shown in Figure 3. Between 10 to 30 minutes of exposure at 400°C the specimen shrank the most. After 20 minutes shrinkage largely ceased and one can presume that calcination likewise had peaked and was decreasing. With the exception of length change, engineering properties were measured after 15 minutes and after 60 minutes of exposure. The major changes in the structure of the gypsum board may have occurred at intermediate times.

Only 60-minute exposure properties are reported herein. As shown in Figure 3, 0.1% shrinkage occurred at 200°C and 300°C followed by increased shrinkage between 300°C and 400°C. Shrinkages increased as expected from a 15 minute exposure to a 60 minute exposure.

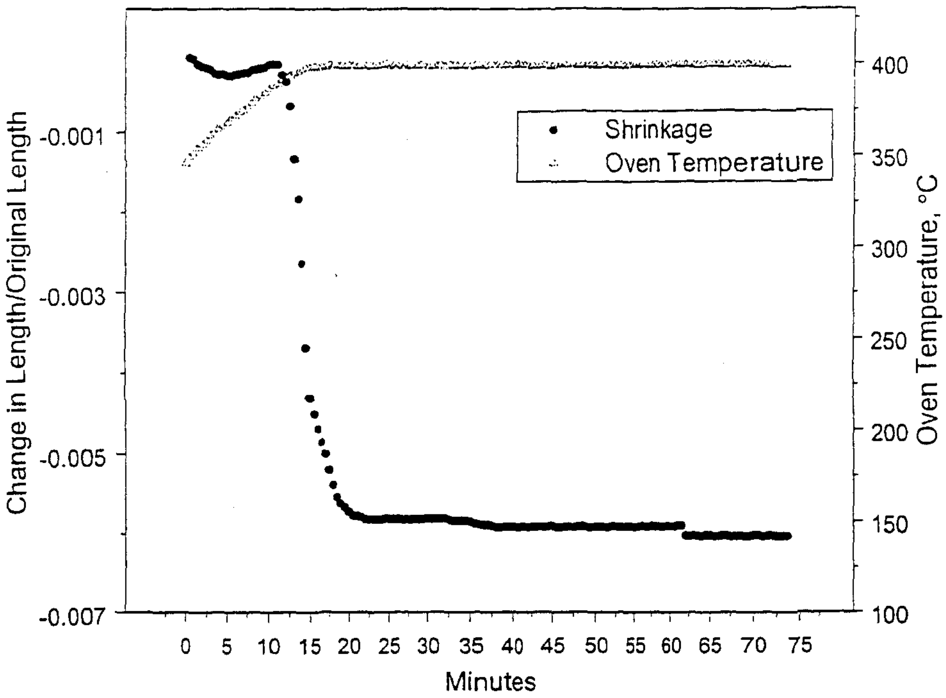

Figure 2. Typical Shrinkage Response of Type X Gypsum Board with 400°C Exposure

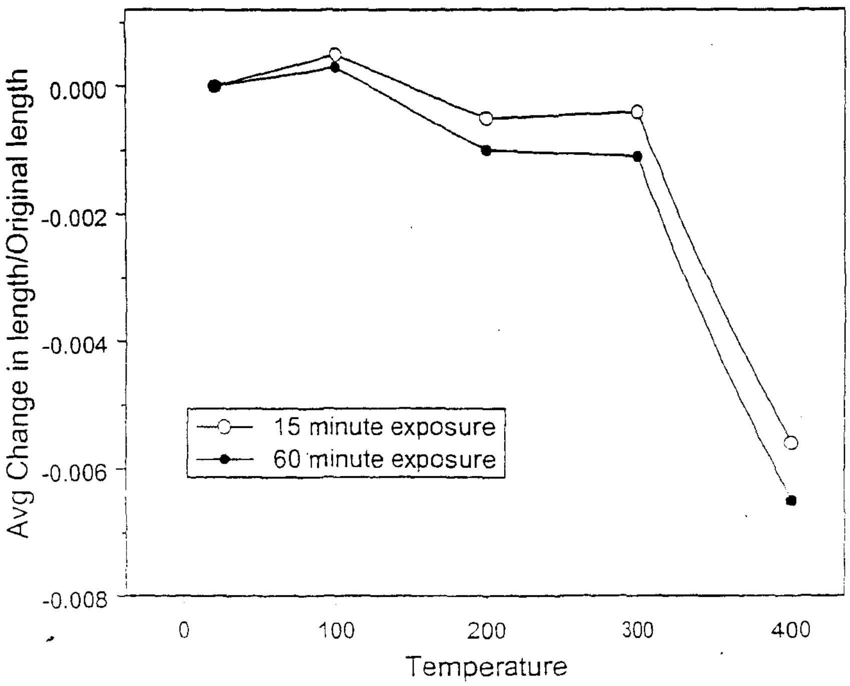

Figure 3. Average Thermal-Induced Shrinkage Strain for 15.9-mm Type X Gypsum Board

Gypsum board contains approximately 21% water by weight and thus as calcination occurs the mass of the board is reduced. We found that after a 60-minute soak period at 100°C that only 3% of the original board weight was lost. For comparison, Harmathy[4] found the mass at 100°C reduced by about 6% of original room temperature mass, with no significant changes from 200°C through 600°C but his exposure conditions were not revealed. At 200°C, we observed a 16% loss in mass that increased to 22% at 400°C (Figure 4). This observation is consistent with complete calcination and loss of all moisture.

Loads and deflections from three-point bending tests were used to evaluate modulus of elasticity and bending strength. The specimen size, 177.8 mm by 50.8 mm, was selected to meet the constraints of the test chamber, resulting in a short beam where shear deformations were several percent of the total deflection. Shear effects were considered by treating the gypsum board as an isotropic material with a Poisson's ratio of 0.3. This resulted in a shear modulus that was 38% of the modulus of elasticity. The brittle nature and low tensile strength of the gypsum board specimens rendered tension tests impractical. All tests were conducted with the paper intact on both faces of the gypsum board as it is used in service.

The bending strength of the gypsum board specimens was defined as the maximum load achieved in the initial linear portion of the load-displacement plot. Often significant additional load was resisted after the first crack formed. Maximum loads ranged from 5% to 150% greater than that associated with load to first crack depending on temperature. This indicates that the gypsum has reserve structural capacity after cracking but if hot gasses penetrate the cracks the practical significance of this reserve capacity may be moot.

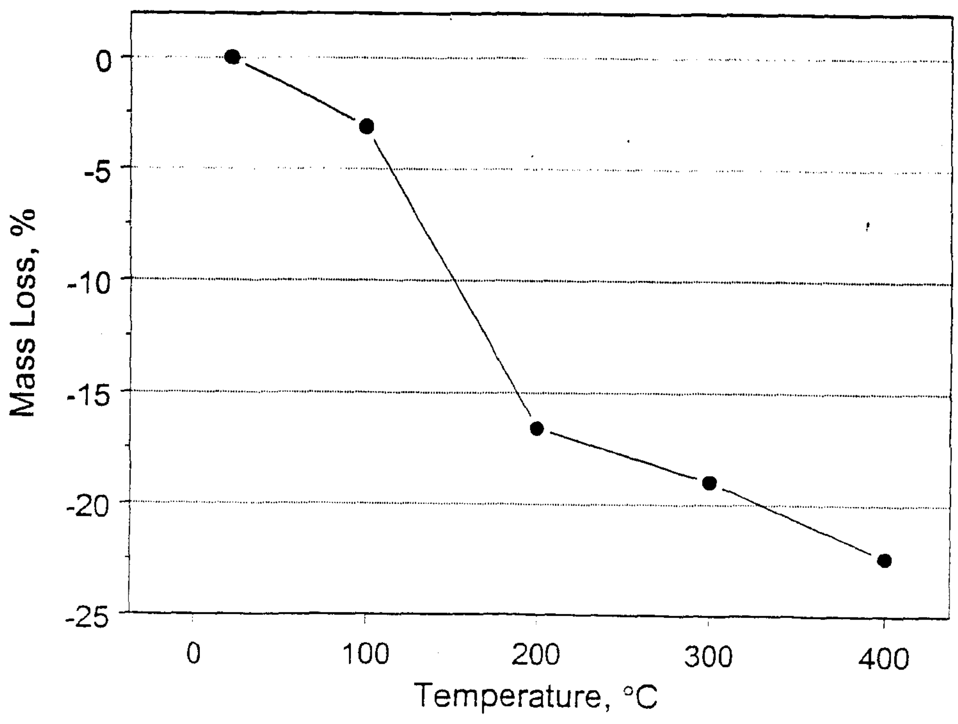

Figure 4. Average Mass Loss After 60 Minutes of Exposure

The strengths and bending stiffnesses of the specimens depended on the orientation of the specimen in the original gypsum board panel. When the length of the specimen coincided with the long direction of the panel, the strength and stiffness were significantly higher than they were when the length of the specimen was oriented parallel to the panel width. This distinction was reduced at higher temperatures.

Bending strengths at ambient conditions were in the range of 2.0 to 4.0 MPa depending on specimen direction and other factors. Figure 5 shows the average degrade in bending strength that occurred after 60 minutes of exposure at temperatures up to 400°C. As indicated by the mass loss in Figure 4, calcination is complete by 60 minutes (possibly as soon as 25 minutes from Figure 2) of exposure at 400°C as all available water has been driven off. As expected the bending strength decreases to a value close to zero after 60 minutes at 400°C. Figure 5 shows that the bending strength decreases in a near linear manner for specimens from the short or cross-panel orientation. Contrary to the theory that the alignment of the glass fibers is the cause of strength differences in different directions, we propose that the board strength orthotropy can be attributed primarily to the machine and cross direction properties of the face paper. It is well established the machine direction of paper is significantly stronger and stiffer than the cross direction. We have not established that there is any significant directional bias to the glass fibers in gypsum board although a small amount of unintended bias may exist because of manufacturing methods. With specimens cut from the long direction of the panel, the stronger machine direction of the face paper plays an important role. Between 200°C to 300°C, the paper chars away and the strengthening influence gradually disappears (Figure 4). It was not uncommon in the tests at lower temperatures for the gypsum core to crack but the paper to retain its' integrity allowing the panel to sustain an increase in load. This behavior demonstrated the important structural role of the face paper.

An apparent modulus of elasticity was computed that depended on the gross cross section. The presence of the surface paper on each face of the gypsum board results in a composite section. The separate layers degrade differently as temperature exposure is increased and eventually the paper bums away completely. The gross section was used in this analysis and was assumed to be homogeneous.

The degradation of apparent modulus of elasticity relative to the ambient value to is shown in Figure 6. Ambient modulus of elasticity was in the range of 1.7 to 2.5 GPa. The trend of degradation is similar to that of mass loss. After 60 minutes of exposure at 200°C, the loss in modulus of elasticity in the gypsum matrix is essential complete. Sufficient adhesion to the reinforcing glass fibers continues however and even at 400°C some stiffness is retained.

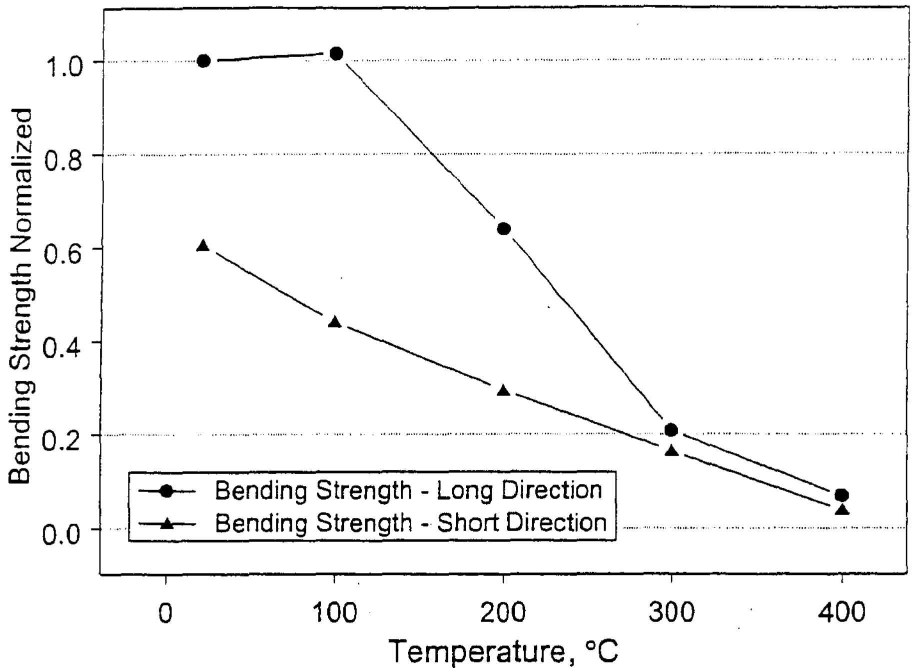

Figure 5. Degrade in Bending Strength after 60 Minutes of Exposure

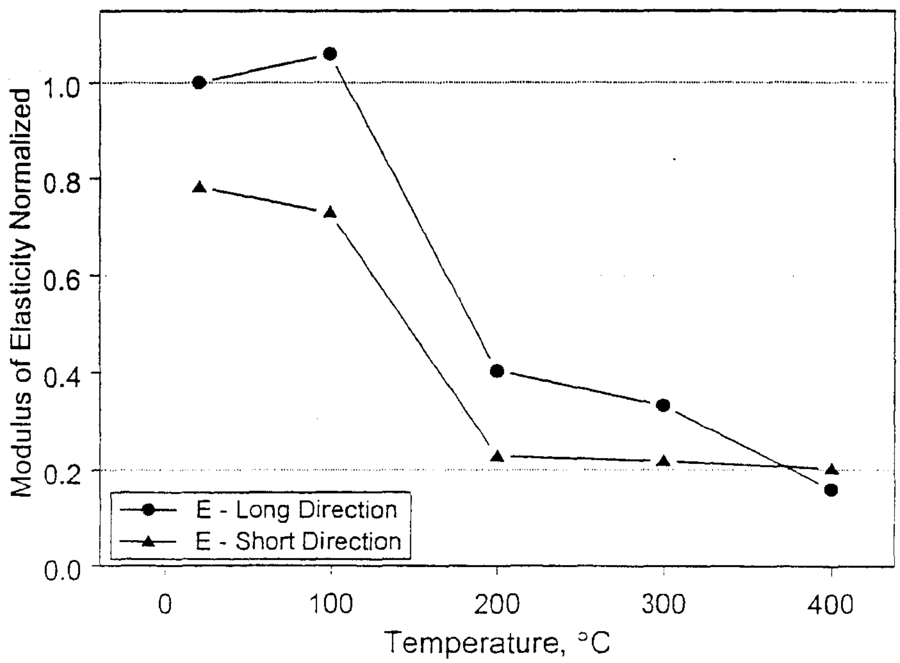

Figure 6. Degrade in Modulus of Elasticity after 60 minutes of Exposure 4

The objective of the small scale gypsum board mechanical tests was to establish engineering properties of gypsum board that would enable the evaluation of equations 2 and 3. These equations will be evaluated through the development of a computer-based structural analysis model that accounts for the unique behaviors of a light-frame assembly where gypsum board is attached with screws to wood members. Such a model will require inputs of properties. The load-deflection behavior and stress development in such an assembly can be highly nonlinear, but for first order calculations with a linear-elastic analysis, values as shown in Table 1 are recommended. Preliminary calculation has shown that temperature on the unexposed side of the gypsum board is a practical temperature value upon which to base property assignments. The property values in Table 1 reflect the degrade trends shown earlier. Coefficient of thermal expansion reflects the tendency of the gypsum to first expand at temperatures below 120°C followed by shrinkage (Fig. 2).

Table 1. Engineering Average Properties of 15.9-mm Type X Gypsum Board for Structural Modeling

Temperatrue unexposed face of gypsum board (°C)	Mass per Volume (Kg/m^3)	Modulus of Elasticity (GPa)		Bending Strength (MPa)		Coeff. of Thermal Expansion (mm/mm °C)	
		Along Panel	Across Panel	Along Panel	Across Panel	Along Panel	Across Panel
23	700	2.50	1.75	3.79	2.25	-	-
100	680	1.41	1.15	3.76	1.64	2.6×10^{-6}	3.9×10^{-6}
200	590	0.94	0.48	2.37	1.09	-5.1×10^{-6}	-6.2×10^{-6}
300	570	0.58	0.54	0.93	0.66	-3.2×10^{-6}	-5.4×10^{-6}
400	545	0.47	0.52	0.26	0.14	-1.6×10^{-6}	-1.9×10^{-6}

To evaluate Eq. 2 the properties in Table 1 are necessary, but are insufficient to evaluate $\sigma_{screw\ transfer}$ term, stresses resulting from the transfer of forces from the wood members through the screws or other attachment scheme and $\sigma_{shrinkage}$, stresses resulting from the restraint caused by the screws or other attachment scheme to the shrinkage of the gypsum board. Tests are in progress to evaluate the load-slip properties of the attachment of gypsum board and wood structural members by common drywall screws. There is little doubt that at ambient or low elevated temperatures that stress transfer through the screws is significant and the screws not only hold the gypsum board in place but also incorporate the gypsum board into the overall load resisting characteristics of the assembly. As temperatures increase and the gypsum board approaches calcination, other investigators have argued that localized crushng around the screws renders this stress transfer to be negligible. Yet, as temperatures increase and the gypsum board begns to shrink, it is these screws that resist this shrinkage and can place the gypsum board into a state of tension combined with the other stresses that may occur. Preliminary analysis of a mock ceiling assembly and Equation 1. suggests that of the total stress in the gypsum when temperatures reach 400°C on the unexposed side of the gypsurn. approximately 75% is associated with $\sigma_{bending}$, 5% is associated with $\sigma_{screw\ transfer}$ and 20% is associated with $\sigma_{shrinkage}$, More research is needed to fully explain the complex behavior of gypsum board in a structural assembly and our work continues.

CONCLUSIONS

The longevity of light-frame wood and steel partitions and ceilings in a fire depend on maintaining the gypsum board membrane over framing members. We propose that the longevity of the integrity of the gypsum board membrane is a function of the stress conditions and transient strength characteristics of the gypsum. Gypsum board is not an isolated and independent fire resisting component but instead is an integral part of load bearing wall and ceiling structural assemblies. We have begun an investigation to measure gypsum board engineering properties and to develop an analysis procedure to evaluate the structural response of gypsum board such that its longevity can be predicted. Tests completed reveal the complete loss of moisture (calcination) of the gypsum board occurred prior to 60 minutes of exposure at 400°C. The largest decreases in mass and shrinkage occurred between 100°C and 200°C. Bending strength decreased almost linearly as temperature increased and approached 0 at 400°C. Significant residual strength occurs at low temperatures after first crack. Modulus of elasticity based on an assumed homogenous section decreased the most from 100°C to 200°C as calcinations was in-progress. This research reveals the engineering properties of gypsum board such that gypsum board fire barriers can advance from simple prescriptive construction requirements to engineering design.

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