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Structural materials, fire and protection

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Abstract
Any material that can be used in the construction of a building is called building material. Concrete, reinforced concrete, steel, aluminum, wood, tile, plaster, etc., are known as building materials. Fire is a chemical event that occurs as a result of the combination of matter with heat and oxygen. Fire protection is the study and practice of reducing the undesirable effects of destructive fires. It includes the behavior, suppression, and investigation of the fire. In this study, building materials such as steel, concrete, and wood were examined, and then the protection of building materials using fire-resistant materials and fire systems was emphasized.

Keywords: Structural materials, Fire protection, Steel, Concrete, Wood

1. Introduction

Facilities such as buildings, bridges, roads, tunnels, dams established on land or water for public works or settlement and their underground and aboveground constructions are called structures. Any material that can be used in the construction of a building is called building material. Concrete, reinforced concrete, steel, aluminum, wood, tile, plaster etc. are known as building materials. Fire is a chemical event that occurs as a result of the combination of matter with heat and oxygen. In order for combustion to occur, matter, heat and oxygen (air) must be together. The following measures should be taken to prevent fire in structural terms: 1. Non-combustible or non-combustible building materials should be used in buildings, 2. Fire sections should be created to prevent the spread of fire, 3. Precautions should be taken to prevent leakage from the wall to prevent the spread of smoke, 4. Short fire escape routes protected from the effects of fire should be provided, 5. Igniter and combustible Material sources should be stored in separate places, 6. Fire extinguishers should be kept in working condition for fires that may occur at any time. The purpose of this research is to investigate the structural materials including steel, concrete and wood as well as the protection of structural materials using fire resistive materials as well as systems from fire.

2. Response of physical materials to fire

Flammability rating is an extensive and vital fire grouping of structural materials. Flammable materials will not solitary worsen at greater temperatures, nonetheless will also catch fire and blister, thus totaling to the fuel content through a fire. Non-combustible materials worsen at the elevated temperatures of a fire, however typically do not burn in the construction fires. Traditional structural materials are wood, concrete and steel. Wood is the solitary flammable material of those three, steel and concrete do not. In both cases, noticeable deterioration occurs in the thermal and mechanical possessions of all structural materials at long-term high temperatures. Therefore, this possessions degradation and the belongings of huge thermal distortions on the burden bearing competences of materials through a fire are two significant belongings that should be comprised in a building's fire resistance analysis or engineering. Ultimate strength and material ductility at elevated temperatures, or supreme mechanical stress, can manage the physical veracity of these frames and joints, significantly restricting thermal expansion, where thermal stresses will be approximately equal to mechanical stress but vice versa.

Physical fire retort can be evaluated in one of three ways: first, special purpose fire tests; secondly, with heat transfer and basic calculation techniques of discrete physical components in a basic way; or third, over more extensive and complex demonstrating of fires. The most communal standard fire experiments implicitly comprise material and fire guard specifications in resulting discrete member or assemblage ratings. Typical fire resistance rating times are founded only on material temperatures that do not exceed a certain perilous temperature. More truthful, complete fire experiments of multi-storey frames or car parks, for example in England [1], are performed comparatively rarely because of their high cost. Application of advanced fire confrontation calculations will need a clearer depiction of material possessions at raised temperatures.

2.1. Steel

Steel is a non-combustible material obtainable in a variety of artefact sorts. However, disclosure to high temperatures causes a provisional reduction in the strength and hardness of the steel. During protracted fire exposure, the strength and hardness of steel decreases. After more than 15 minutes of exposure to temperatures in excess of approximately 600°C, unprotected steel bends quite visibly. At such in elevation temperatures, steels' structure moreover endures a transformation. Steel exposed to a hot and protracted fire will have widespread destruction. However, steel that is not unprotected to very in elevation temperatures for a long time will recover its unique thermomechanical possessions. Therefore, such elements can be revamped. If the steel has not surpassed the temperature of 600°C, it will come back to its unique mechanical possessions after cooling. The stress-strain curvatures for rolled steel at dissimilar high temperatures are displayed in Figure 1. Cold formed and prestressed steel will show differential strength decrease (Figures 2 and 3). However, at temperatures above 700°C, both yield and ultimate strength reduction occur in steel. The scattering, linear reduction equations for yield and ultimate strength reductions for various steel types are shown below [Eq. (1)].

$$k_{y,T} = \frac{905 - T}{690}; \text{structural steel}$$
$$k_{y,T} = \frac{720 - T}{470}; \text{reinforcing steel} \qquad \text{Eq. (1)}$$
$$k_{y,T} = \frac{700 - T}{550}; \text{prestressing steel}$$

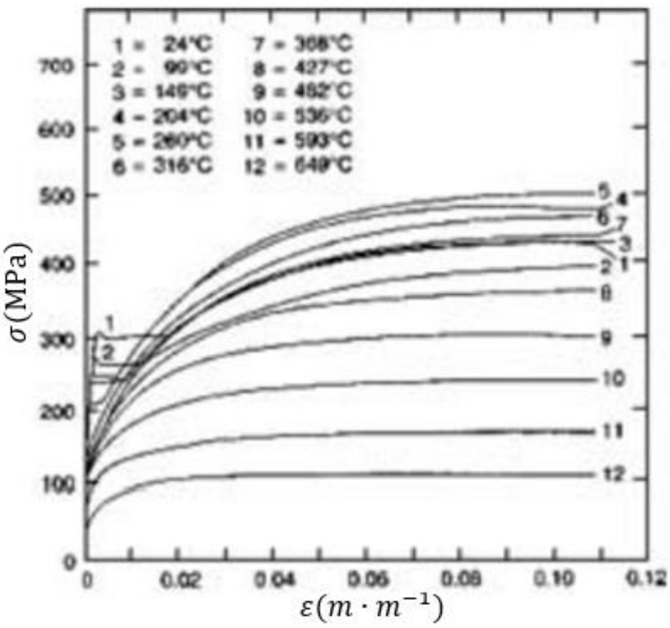

Figure 1. Strain-stress curvatures for hot rolled steel at high temperatures [2]

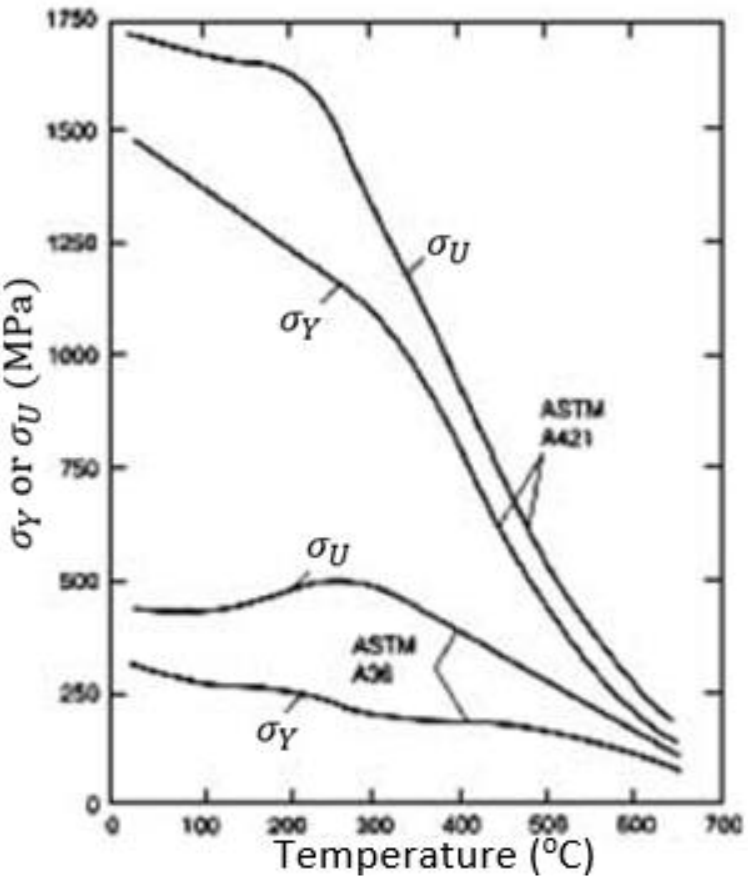

Figure 2. Tensile and yield strengths for structural steel (ASTM A 36) and prestressing steel (ASTM A 421) at high temperatures [2]

Elastic modulus E, which influences elastic distortions and elastic buckling, likewise decreases with temperature. Small elastic deflection considerations can often be neglected, as important structural fire possessions happen in the great deflection and nonlinear plastic variety. Figure 4 displays the temperature deviation of elastic modulus for structural steels and strengthening bars. Once more, notwithstanding the distribution of data for certain steel types and tests, an empirical design equation [Eq. (2)] can be expressed for the residual elastic modulus fraction of steel comparative to the worth at ambient temperature (20°C):

$$k_{E,T} = 1.0 + T/[2000 \ln(T/1100)] \qquad 0 < T \leq 600°C \qquad \text{Eq. (2)}$$
$$k_{E,T} = 690(1 - T/1000)/(T - 53.5) \qquad 600 < T \leq 1000°C$$

Strength and elastic modulus are fundamental mechanical possessions related to fire engineering. By means of this data shows, a steel element will drop semi of its strength and hardness at what time its temperature extents 550 to 600°C. Three important thermal possessions are also convoluted in demonstrating the performance of steel under fire exposure: specific heat, thermal extension coefficient, and thermal conductivity. The thermal extension coefficient or thermal strain ΔL/L manages the quantity of thermally tempted enlargement ΔL in an element. This possessions upsurges with temperature. The coefficient of thermal extension for steel is typically reserved as 11.5 x 10^{-6}/°C at ambient temperatures. At elevated temperatures, the thermal strain can formerly be approached for the design with the linear purpose [4]:

$$\Delta L/L = 14 \times 10^{-6}(T - 20) \qquad \text{Eq. (3)}$$

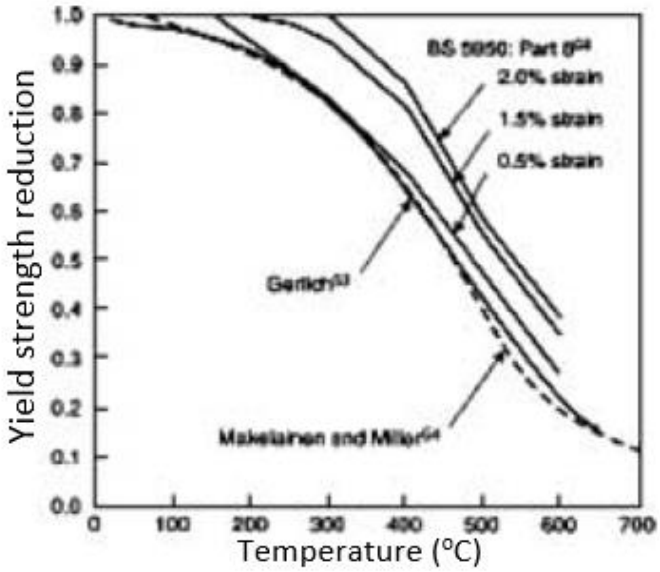

Figure 3. Decrease of the yield strength of cold-deformed steel at raised temperatures [3]

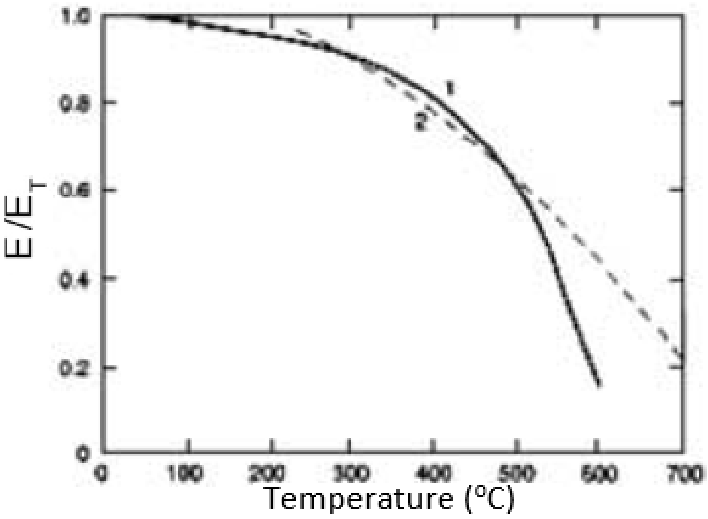

Figure 4. Outcome of temperature on the elastic modulus of structural steel and strengthening pieces [3]

The density of the steel leftovers perpetual at a temperature of 7850 kg/m3. The steel's specific heat cp is reserved as a fixed worth of 600 J/kg·°C, nonetheless essentially ranges from 400 to 700 and reaches its uppermost worth at 700°C (Fig. 5). Figure 5 also shows the thermal conductivity of steel in W/m·°C, which decreased from 54 at 0°C to a least worth of 27.3 at 800°C. Preceding reporting was restricted to mutual steel yields utilized for structural construction, for example these provided in AISC [5] and AISI design criterions and guidelines.

2.2. Concrete

Concrete is a non-combustible material with comparatively stumpy thermal conductivity. Its physical design frequently consequences in weightier and extra enormous elements associated to the steel frame, providing a desirable heat sink for absorbing heat from the fire. Owing to this thermal mass consequence and main burden bearing competences, concrete has been and endures to be utilized for thermal lining and/or fire obstructions. However, akin to additional building materials, concrete similarly involvements possessions degradation in addition to noticeable cracking or blistering impairment with growing temperatures. The possessions changes depend on the weight density, compressive strength level, water-cement ratio and sort of aggregate and reinforcement in the concrete.

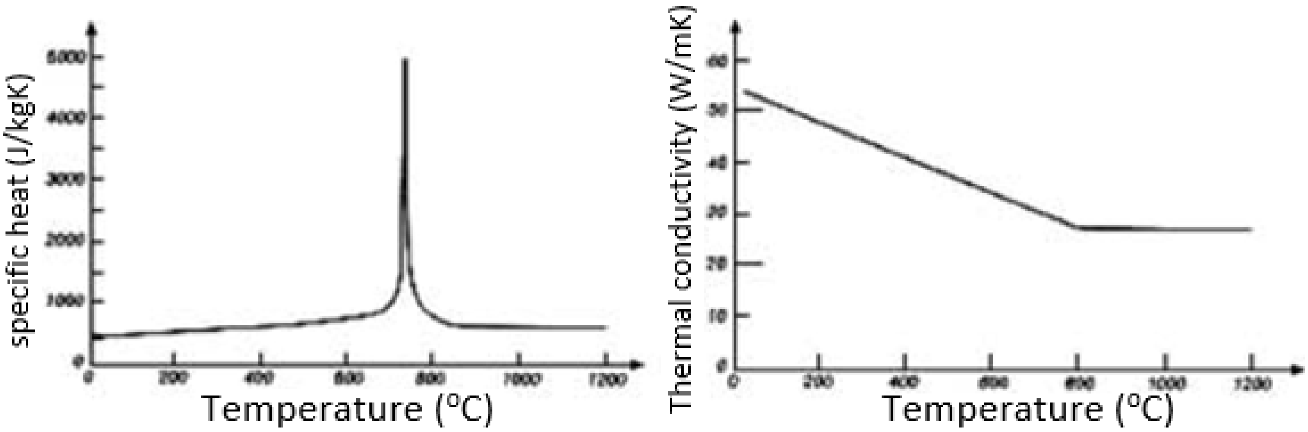

Figure 5. Thermal conductivity (W/mK) and specific heat (J/kgK) of steel at raised temperatures

Table 1. Smallest thickness and protection for reinforced concrete associates

		Beams	Columns	Slabs	Walls
0.5 hours	Width	80	150	75	75
	Cover	20	20	15	15
1.0 hours	Width	120	200	95	75
	Cover	30	35	20	15
1.5 hours	Width	150	250	110	100
	Cover	40	30	25	25
2 hours	Width	200	300	125	100
	Cover	50	35	35	25
3 hours	Width	240	400	150	150
	Cover	70	35	45	25
4 hours	Width	280	450	170	180
	Cover	80	35	55	25

Concrete constructions can be unreinforced, reinforced, prestressed and composite. Where concrete is usually utilized with steel, temperatures determine the fire confrontation scores of the concrete element. The distance from the concrete cover or inner steel to the outer concrete surface delivers fire fortification. Table 1 displays the scope value requirements for a reinforced concrete column. The 2200 kg/m^3 is the density of normal weight concrete (NWC), while the density of lightweight concrete (LWC) is about 0.67 of this worth. These densities remain effectively stable up to a temperature of 800°C, where the usual weight density starts to degrade speedily by about 25 to 50 %. At ambient temperature, the concrete compressive strength fc' can range from 20 to 50 MPa. For LWC, this higher limit strength is solitary 40 MPa depending on concrete mixture properties for example water-cement ratio, concrete age, aggregate amount and type. The modulus of elasticity Eo at room temperature can range from 5000 to 35,000 MPa. The 840 J/kg·°C is the specific heat of concrete for LWC and ranges from 1000 to 1200. LWC is preferred for fire resistance due to its lower thermal conductivity. All these experiential data have been abridged to mathematical expressions and shortened. Buchanan [6] delivers the subsequent equations [(3) to (6)] founded on BS 8110 and/or EC2 (1993) for concrete compressive strength, elastic modulus and thermal strain differences, correspondingly.

$$k_{c,T} = 1.0 \quad \text{for T} < 350°\text{C}$$
$$k_{c,T} = (910 - T)/560 \quad \text{for T} > 350°\text{C} \tag{3}$$

$$k_{c,T} = 1.0 \quad \text{for T} < 500°\text{C}$$
$$k_{c,T} = (1000 - T)/500 \quad \text{for T} > 500°\text{C} \tag{4}$$

$$k_{E,T} = 1.0 \quad \text{for T} < 150°\text{C}$$
$$k_{E,T} = (700 - T)/550 \quad \text{for T} > 150°\text{C} \tag{5}$$

$$\Delta L/L = 18 \times 10^{-6}T \quad \text{for siliceous aggregate concrete}$$
$$\Delta L/L = 12 \times 10^{-6}T \quad \text{for calcareous aggregate concrete}$$
$$\Delta L/L = 8 \times 10^{-6}T \quad \text{for lightweight concrete} \tag{6}$$

An even modest set of concrete material possessions is provided in ASCE 29–99 [7]

Table 2. Concrete material possessions

	Normal weight[a]	Structural lightweight[b]
Thermal conductivity, k_c	0.95 Btu/h-ft-°F (1.64 W/m·K)	0.35 Btu/h-ft-°F (0.61 W/m·K)
Specific heat, c_c	0.20 Btu/h-ft-°F (0.84 kJ/kg·K)	0.20 Btu/h-ft-°F (0.84 kJ/kg·K)
Density, ρ_c	145 lb/ft³ (2323 kg/m³)	110 lb/ft³ (1762 kg/gm³)
Moisture content, m (percent by volume)	4	5

a. Usual mass concrete is carbonate or siliceous aggregate concrete.
b. Structural lightweight concrete is lightweight concrete, with a minimum density of 110 lb/ft³ (1762 kg/m³)

High strength concrete (HSC) usually has a compressive strength of 55 MPa, has unique temperature dependence unlike normal NWC or LWC. HSC is more vulnerable to volatile fragmentation that can happen when unprotected to severe fire circumstances. The specific heat of HSC is given in Figure 6. Fiber strengthened concrete signifies additional concrete material. Intermittent steel and PP fibers are included into the concrete mixture to increase its ductility and strength.

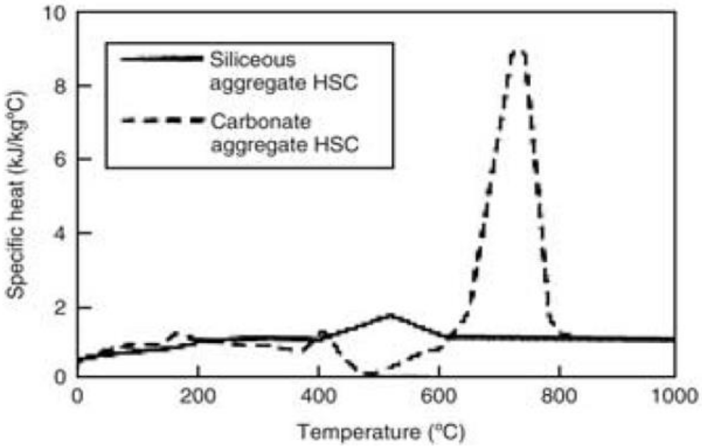

Figure 6. Specific heat of HSC [7]

2.3. Wood

Wooden structure can be in two different categories as heavy and light. Wood is mainly utilized in housing and single-story structure. It is a flammable and orthotropic material with diverse possessions in transverse and longitudinal directions depending on the grain direction of the wood. The strength along the wood grain is much greater than that perpendicular to it. It is also well known that the strength of wood under long-term loads decreases over time. The image of wood damage subsequently a severe fire is revealed in Figure 7. Moisture content and grain direction are the main factors that distress the in elevation temperature possessions of wood. The dry density of clear wood at ambient temperature varieties from 300 to 700 kg/m3; it declines by 10 % at 200°C and then suddenly decreases by 80 % at around 350°C.

Figure 7. Wood fire damage

The reduction of tensile strength with temperature is alike to compressive strength, however somewhat less speedy. Effectually, at temperatures of 300°C and above, most of the strength and hardness of wood is vanished. The association of thermal conductivity with temperature is illustrated in Figure 8 and specific heat is given in Figure 9. The increase of around 100°C signifies the heat essential to vaporize the internal dampness in the wood.

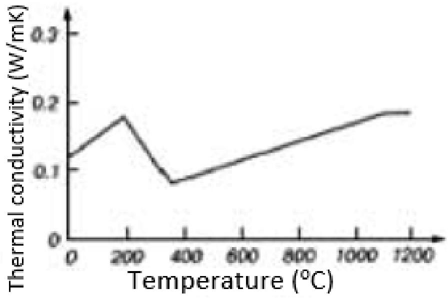

Figure 8. Changing of thermal conductivity of wood with temperature [3]

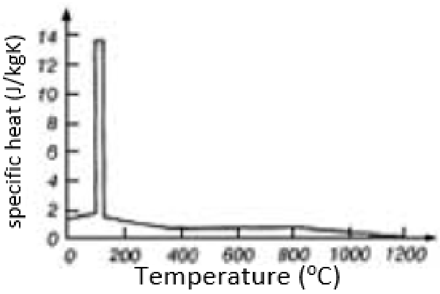

Figure 9. Changing of specific heat wood with temperature [3]

The thermal expansion coefficient varieties from (3.2 to 4.6) x 10^{-6}/°C sideways the wood grain and across the grain (21.6 to 39.4) x 10^{-6}/°C. When wood is burned, the wood surface catch fire and creates a stratum of charcoal that efficiently protects the solid and flammable wood intimate. This coal stratum width consequence in a decrease in the actual wood cross-section obtainable for physical burden confrontation. Connections for wooden elements are usually made with metal fasteners. These wooden joints behave very differently from exposure to fire. It has been observed that metal fasteners such as nails and screws work well under high temperature contacts if they are sufficiently endangered from fire by protecting the wood itself.

3. Protection of structural materials from fire

To control harmful temperature, supplementary isolating materials are added as cladding, enclosure, cover or shielding membrane. Fire protection is characteristically dignified by a fire resistance rating period in a typical fire test for example ASTM E 119. Shielding materials and approaches for fire confrontation arise in numerous dissimilar forms and are willingly available commercially. The most commonly used insulation materials are fiber and aggregate coatings. They are called spray applied fire resistant materials (SFRMs). The finest energy fascinating materials are plaster and concrete. Inflatable coating materials functional as paint enlarge when exposed to great temperatures and form a protecting stratum. It is recommended that the assortment of protection type for fire guard be combined with architectural, structural, economic and construction applications and product availability.

3.1. Fire-resistive materials

3.1.1. Gypsum

Gypsum is a non-combustible material manufactured in the plane form sheets or gypsum, consisting of about 21 % by weightiness of chemically united water. This water composition significantly donates to the effectiveness of gypsum yields as a fire-resistant obstacle [8].

During a fire exposure, gypsum plaster effectively retards heat conduction from the basis to the endangered physical participant (Fig. 10). At what time wood or steel structural adherents protected by plaster are unprotected to a fire, this sluggish water release procedure recognized as calcination deeds as a thermal obstacle till all interior water has vaporized. After calcination is complete, the calcined plaster continues to act as a physical shield.

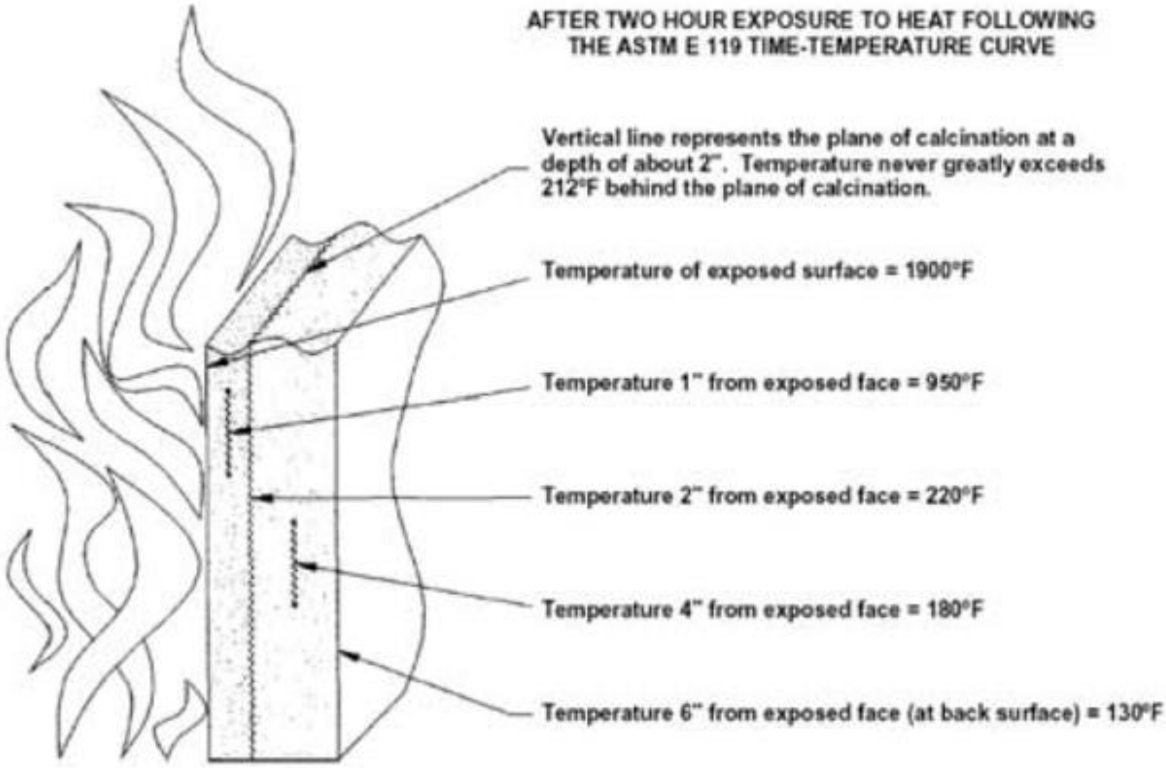

Figure 10. Fire guard characteristics of Type X gypsum board [8]

The ASTM C 36 standard defines two sorts of drywall, systematic and enhanced Type X. Type X, apiece as long as varying degrees of fire confrontation. Drywall, which does not contain a special fire-resistant additive, is called ordinary plaster. Usually fire resistant Type X or enhanced Type X plasterboard is used. Type X board core covers unusual spices to additional increase the natural fire confrontation of regular gypsum. Some basic possessions of gypsum board for example specific and potential heat, and conductivity are specified in Table 3.

3.1.2. Spray-applied materials

Spray smeared fire resistant materials are coverings smeared to the exterior of the steel element. Suitable product and site quality control, scrutiny and practices are crucial features in the fruitful fire enactment of the artifact and assemblage. Standard fire test processes need that the nominal assemblage be constructed and maintained according to these printed endorsements. Upon fruitful accomplishment of the test, the conformation of the assemblage in addition to the producer's endorsements for the artifact request process develop portion of the "inventory" for a specific design.

Numerous ASTM criterions address the quality control and enactment of related fire guard products. For instance, SFRM usually utilized to guard structural steel, the results will also pass SFRM standard tests such as ASTM E 84, ASTM E 605, ASTM E 736, ASTM E 759, ASTM E 760, ASTM E 761, ASTM E 859, ASTM E 937. Existing checkup processes are not continuously sufficient to confirm the appropriate chemical composition, density, and thickness of the fire protection material. Unfortunately, there are no existing standards by which various fire protection products can be evaluated for long-term durability, resistance to aging, corrosion, vibration, abrasion, etc.

Table 3. Selected gypsum board properties [3, 8]

Surface Burning Characteristics (Independent of thickness) (ASTM E 84—CAN/ULC-S102)		
Board type	Flame spread	Smoke developed
Gypsum wallboard	10–15	0
Gypsum lath	10	0
Gypsum sheathing	10–20	0

Fire Resistance (ASTM E 119—CAN/ULC-S101-M)
See the Gypsum Association *Fire Resistance Design Manual*.
Noncombustibility (core) (ASTM E 136—CAN/ULC-S114-M)
Pass

Potential Heat (From NFPA 220, Appendix C)			
Thickness in. (mm)	Board type	Potential heat, weight basis	
		(Btu/lb)	(kJ/kJ)
3/8 (9.5)	gypsum lath	310	721
3/8 (9.5)	gypsum wallboard	760	1770
3/8 (9.5)	gypsum wallboard, paper removed	−270	−628
1/2 (12.7)	gypsum wallboard	650	1512

3.1.3. Concrete

Normal concrete is the weightiest inorganic material with a density reaching from about 100 to 150 lb/ft3 for light and usual mass aggregates, correspondingly. Concrete often functions as a fire defensive material. The finest energy fascinating materials are gypsum and concrete. Apiece of these energy fascinating materials also releases water of crystallization when unprotected to great temperatures. As said by Lie [9], the fire resistance period of concrete increases by about 3 % for every percentage of water trapped. Though plaster is loftier in this respect, concrete delivers a much harder and more sturdy guard. Concrete and other high-density spraying materials are more tough as long-term fire guard.

3.1.4. Masonry

Masonry can be utilized in much the similar way as concrete for mutually load-bearing and fire guard requests. Likewise, its comparatively heavy mass and greater prices associated to the lighter SFRMs or gypsum yields frequently make masonry a fewer gorgeous selection in terms of budget for humble construction fire guard requirements.

3.2. Fire-resistive systems

Special systems can be utilized to switch and slow the temperature increase in physical frame materials when unprotected to warming. These are entitled fire protection materials or fire resistant systems. Blaze protecting and flooded columns are two of the inventive schemes that have been fruitfully utilized for fire guard of steel enclosed structures.

3.2.1. Water-filled columns

A singular system that can be utilized to provide fire guard is water-cooled columns. This idea depends upon the hydraulics and thermodynamics of cold water circulating inside the steel columns when unprotected to a fire. The apparatus supplies water and retains the structural steel itself cold ample to prevent strength and hardness deprivation. Such liquid filled columns can uphold limitless fire confrontation providing liquid source and exchange are provided.

3.2.2 Flame shielding

The opinion of flame protection is based on if a physical obstacle against straight flame strike to the building element to be considered fire resistant. Flame shielding through and around the window opening delivers some air/distance parting amid the fire and the part, protecting the system from exposure to fire temperatures.

The design is deliberated suitable for fire safety if the steel temperature is fewer than the perilous temperature of 1000°F. The location of appropriate additional flame protection can help prevent more direct flame strikes to external load-bearing elements [10].

4. Application of fire resistance ratings

Building codes applied in various countries of the world utilize fire confrontation as part of the fire guard necessities for structures. In some republics, other forms of fire guard, for example sprinklers, are essential and may substitute or replace fire resistant structures. However, the construction and protection of structural systems must be given serious consideration when designing a new construction or upgrading an obtainable facility. Few examples of structural collapse due to fire have been described and this, combined with protection requirements when evacuating occupants in a building or awaiting assistance, requires the use of fire resistant construction. Therefore, a comprehensive thoughtful of the materials utilized in this request in addition to their fire contact enactment must be achieved in order to exploit their usage while provided that life and stuff guard against fire [3].

5. Conclusions

Any material that can be used in the construction of a building is called building material. Concrete, reinforced concrete, steel, aluminum, wood, tile, plaster etc. known as building materials. Fire is a chemical event that occurs as a result of the combination of matter with heat and oxygen. The consequent inferences can be drawn from the existing research:

a) Steel, concrete and wood are mentioned as outdated construction materials. Among these three, the solitary flammable material is wood, not steel and concrete. In both cases, visible damage/deterioration and deterioration occur in the mechanical and thermal possessions of all construction materials at long-term high temperatures.

b) To control harmful temperature, additional insulation materials are added as elevation, cladding, enclosure, envelope or protective membrane throughout a fire contact in the main load-bearing members of the physical framework. The most commonly used insulation materials are mineral fiber and expanded aggregate coatings.

c) Building codes applied in various countries of the world usage fire confrontation as part of the fire fortification necessities for constructions. In some nations, additional systems of fire guard, for example sprinklers, are essential and may fire resistant structures. However, serious consideration should be given to the construction and maintenance of structural systems when designing a new construction or upgrading a current facility.

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