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ROLE OF FIRE RESISTANCE ISSUES IN THE COLLAPSE OF THE TWIN TOWERS

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Abstract

The twin towers of the World Trade Centre suffered significant damage from the impact of the planes, however, they withstood the impact. The severe fires that followed the impact brought down the twin towers, WTC 2 and WTC 1, at different intervals - 59 and 89 minutes respectively following the impact. Thus, fire issues played a major part in the collapse of the twin towers and the role of the various fire resistance issues is examined in this paper.

While the jet fuel from the aircraft was burned off within the first few minutes, the fire temperatures attained in the twin towers was not significantly different from other building fires. However, the fire intensity and heat output generated in the twin tower fires was very much higher than typical building fires. The intense fires ignited by jet fuel, loss of fire defence mechanism, damaged fire proofing and the stressed state of the structural system were the main factors that contributed to the collapse of the towers.

Key words: WTC, Twin Towers, Collapse, September 11, Fire Resistance

1. Introduction

The twin towers, comprising WTC 1 (North Tower) and WTC 2 (South Tower), were the primary components of the seven building World Trade Center (WTC) Complex in Manhattan, New York City. These towers, built in the late 1960's were 110 stories above grade and were the world's tallest buildings for a while. The full occupancy of the towers was about 50,000 people and the tenants included many prominent multinational financial service companies. Therefore, these towers were a major landmark and financial center in New York City.

On September 11, 2001 American Airlines Flight 11, enroute from Boston to Los Angeles was hijacked and slammed into the north tower of the World Trade Center at 8.46 a.m. Shortly thereafter, a second hijacked plane, United Airlines Flight 175, was slammed into the south tower of the WTC. Both airplanes that struck the towers were Boeing 767-200ER aircraft and were loaded with heavy amounts of jet fuel for transcontinental flights (ENR 2002, FEMA 2002).

The first aircraft struck the north face of WTC 1 approximately between the 92nd and 96th floors while the second aircraft struck the south face of WTC 2 between the 78^{th} and 84^{th} floors. The massive impacts from each of the aircraft resulted in severe structural damage at several floor levels in each tower. However, the structures remained standing, at least initially, despite this heavy but localized damage. The subsequent, intense fires that followed further weakened the already damaged structure, resulting in the collapse of the floors, initiated at the floor with the worst fire conditions. The impact load of the collapsing floors on the structure below started a progressive collapse and resulted in the complete collapse of the towers.

An overview of the factors that led to the collapse of the twin towers and the collapse mechanism in each of the towers is detailed in report (FEMA 2002) and is based on the "building performance study" commissioned by the Federal Emergency Management Agency and the American Society of Civil Engineers. In this paper, the role of fire resistance issues in the collapse of the twin towers is discussed. The effect of jet fuel, fire growth, fire defence systems, fire intensity, damaged fire proofing on the collapse towers is examined.

2. Features of Twin Towers

2.1 General.
The two towers, that encompassed 110 stories above grade and 7 stories below grade, had similar features in many respects. Each building had a square floor plate, 207 feet 2 inches long on each side, chamfered 7 feet at each corner. The floor space at each storey level was about 40,000 sq. feet and in total, the twin towers provided more than 10 million square feet of office space. One of the unique features in the design of the towers was the core and elevator system. In the center of each building a rectangular service core, measuring 87 feet by 137 feet, housed 3 exit stairways, nearly 100 elevators, and 16 escalators. The roof height of WTC 1 was 1368 feet tall while the roof height of WTC 2 was 1360 feet. Figure 1 presents a typical floor plan and elevation for the towers. A brief description of structural and fire protection design features is highlighted here. Full details of the various design features can be found elsewhere (FEMA 2002).

2.2 Structural System.
WTC1 and WTC 2 were similar buildings but not identical. The north tower, WTC 1, supported a 300-foot-tall television and radio transmission tower. In the south tower, the service core was oriented north to south, while in the north tower the service core was oriented east to west. In addition to these basic configuration differences, the structural design of the buildings to resist wind loads considered the shielding effects each tower produced on the other, resulting in somewhat different distributions of design wind pressures and therefore somewhat different members in the lateral-force-resisting system of each building.

The WTC buildings were built as a unique structural system known as "tube tower", with stiff exterior walls and columns, and the gravity load-bearing frame at the central core, connected by deep spandrel beams to minimize horizontal deflection. The main architectural design feature of the buildings was the vertical fenestration, the predominant element of which was a series of closely-spaced tubular columns. On typical floors, a total of 59 of these 14-inch-square tubular columns were spaced at 3 feet 4 inches on center across each building face, with an additional column present at the center of each of the chamfered building corners. At the building base, adjacent sets of three columns tapered to form a single massive column, in a graceful arch-like formation. Adjacent columns were interconnected at each floor level by a 52-inch-deep spandrel plate. The resulting configuration of closely-spaced columns and deep spandrels created a three-dimensional moment-resisting frame that extended completely around the building perimeter. This perimeter system acted as a wind bracing to resist all overturning forces, with the central core designed to take only gravity loads of the building.

The core columns were a combination of wide flange shape and box-section columns with cross-sections measuring 14 inches wide by 36 inches deep and having wall thicknesses as large as 3 inches. The grade of steel and thickness of the tube walls and spandrels was varied up the height of the structures and with location on the building perimeter, as dictated by the computed gravity and wind stresses.

Floor construction typically consisted of 4 inches of lightweight concrete fill (5 inches in core area) on a 1½-inch 22-gauge corrugated metal deck. Outside the central core, prefabricated trussed steel, 33 inches in depth, spanned the full 60 feet to the perimeter columns and acted as a diaphragm to stiffen the outside wall against lateral buckling forces from wind-load pressures.

Both WTC 1 and WTC 2 buildings were designed to withstand the accidental impact of a Boeing 707 jet aircraft, which was the state of the art aircraft at the time of construction. However, the original design did not account for the fuel carried by such aircraft (Glover 2002).

2.3 Fire Protection Systems.
The fire protection features in each of the towers included sprinklers, smoke control systems, fire detection systems, notification systems and structural fire protection measures. When originally constructed, the twin towers were not provided with automatic fire sprinklers. However, automatic fire sprinklers protection was installed, as a retrofit, circa 1990 (FEMA 2002). Each tower had three emergency fire exit stairways located in the central core of each building.

The passive fire protection to structural members followed the requirements of the 1970 New York City building code (FEMA 2002, Morse 2002). Cement plaster was used to protect the interior face of the perimeter columns, between spandrels, to achieve 3-hour fire resistance ratings. The exterior faces of the perimeter columns as well as the spandrels, floor joists, and core framing were protected with spray-applied insulation materials with thickness sufficient to achieve the required 3-hour fire resistance ratings. Figure 2 shows structural fire protection for a typical column. The fire protection on trusses which initially consisted of spray-applied fire proofing of ¾ inches, was enhanced in 1990's to 1- ½ inches on certain floors of WTC 1 and WTC 2.

A combination of different fire protection materials was used to obtain these fire resistance ratings. Initially the spray-applied coatings contained asbestos fiber materials up to the 39th level of WTC 1. However, due to concerns with asbestos-related health hazards, the asbestos-containing product was later abated and the balance of WTC 1, and all of WTC 2 floors were completed using mineral-fiber-based products (Morse 2002). For stairs and elevator shafts, steel stud walls, with two layers of 5/8 inch type X gypsum board on exterior face and one layer of 5/8 inch type X gypsum wall board on interior face, provided the required 2-hour fire resistance rating.

3. Collapse of Twin Towers

The impact of both aircraft resulted in severe structural damage at several floor levels in each tower. However, the structures remained standing, at least initially, despite this heavy but localized damage. Immediately after the impact, jet fuel ignited on several floors. The intense fires that followed further weakened the already damaged structure, resulting in the partial collapse of floors, initiated at the floors with the worst fire conditions. This vertical impact load caused failure on underlying multi-floor segments of the tower, in which the failure of the connections of the floor carrying trusses is either accompanied by buckling of core columns or overall buckling of the framed tube, probably spanning the height of many floors. The impact load of the collapsing floors on the structure below started a progressive collapse and resulted in the complete collapse of the towers.

The impact of the planes and the ensuing fires were the two most crucial factors that led to the collapse of the twin towers. While the two towers suffered significant damage from the impact of the planes, they withstood the impact. Based on the preliminary analysis FEMA report (FEAM 2002) the conclusion is that in the absence of a severe loading event, the twin towers could have remained standing in a damaged state until subject to significant additional load. However, the severe fires that followed the impact brought down the "twin towers", WTC2 and WTC1, at different intervals - 59 and 89 minutes respectively following the impact. Thus, the fire issues played a major role in the collapse of the twin towers. Some of these issues are discussed in the following section.

4. Role of Fire Resistance Issues

4.1 State of the structural system.

The impact of aircraft on the north face of WTC 1 (between the 92nd and 96th floors) and on the corner of the south and east face of WTC 2 (between the 92nd and 96th floors) caused massive damage to the structural system at impacted floors. The extent of damage was much higher in the case of WTC 2, where core columns were destroyed in the south and east faces. This is because the impact of the jet was on the corner of the south and east face of WTC 2 and the speed of the aircraft was higher (about 590-mph) at the time of impact (FEMA 2002). The aircrafts penetrated into the central core and the debris travelled completely through the structure, thereby causing considerable damage to columns in the central core as well. In all, up to half of the columns along the north building face appear to have been destroyed over portions of a six-storey range in the case of the north tower. Partial collapse of floors at the impacted levels occurred in both WTC 1 and WTC 2.

The twin towers withstood the impact, despite significant damage, due to a highly-redundant structural system and low utilisation ratio (ratio of applied stress to ultimate stress) in exterior columns (Bazant et al. 2002, FEMA 2002). This enabled the structure to redistribute loads to the remaining structural elements and overcome immediate collapse. However, after redistribution of loads, the utilisation ratio in some of the columns, close to the impact zone, reached unity (FEMA 2002). Hence, after the impact the structural members were in a highly-stressed state. In the case of WTC 2 the stressed state of structural elements was much more severe than WTC 1 due to larger impact damage.

4.2 Jet fuel.

Each of the aircraft had about 10,000 gallons of jet fuel on board. About 25 percent of this quantity was consumed in the initial blast and resulting fireball. Another 25 percent of the fuel is believed to have flowed down through elevators and utility shafts in the buildings. The remaining 50 percent of the fuel burned off within the first few minutes (5 to 8 minutes) of the aircraft impact (Rehm et al.2002, FEMA 2002). As the jet fuel burned, the resulting heat ignited office contents, and combustible aircraft contents, at several impacted floors. Therefore, jet fuel, though burned off in the first few minutes, acted as a catalyst in igniting the combustible materials and in generating massive fires at several floors simultaneously.

4.3 Fire growth.

The large quantity of jet fuel that spread across several floors of the building ignited much of the building and aircraft contents. This caused simultaneous fires across several floors at the same time. This generated fire conditions significantly more severe than those anticipated in typical building fires (Yong and Kodur 2000, FEMA 2002). The maximum fire temperatures attained in the WTC fires were in the range of 1,000° to 1,100°C. These temperatures were not significantly different from other typical office building fires. However, the rise in fire temperatures was much faster than those in typical building fires and represented typical hydrocarbon fires with temperatures reaching about 800°C in the first 3 to 4 minutes (ASTM 1993).

In Figure 3 the time-temperature curves from two standard tests and typical building fires based on temperature measurements acquired in experiments involving office furnishing conducted by DeCicco, et al., (1972) in the Hudson Terminal Building (30 Church Street, New York), is compared. Temperature development in the WTC fires in the intial stages is likely to be closer to the ASTM E-1529 curve.

However, the fire size and heat output in WTC fires was much higher than that of typical office building fires. The heat output generated from WTC fires was about 2-5 GW (FEMA 2002, Rehm 2002) and comparable to the power produced by a large commercial power generating station.

4.4 Fire proofing.

Steel-framed buildings depend on fire proofing for its ability to resist the impact of fire (Kodur and Harmathy 2002). The durability (adhesion and cohesion) of sprayed fiber and, to a lesser extent, the cementatious materials, is a problem when subjected to significant impact loads (Morse 2002). In the twin towers the impact of aircraft mechanically damaged much of the spray-applied fire protection, originally present on the structural steel frame, to an extent that much of the steel in the immediate fire area was unprotected (FEMA 2002, Glover 2002). This was especially true in the case of light-weight bar joist trusses and the floor deck since the impact of jets led to partial collapse of ceilings and must have scraped most of the spray-on fire-proofing. The intense fires on several floors, that followed the impact, weakened the bare steel.

4.5 Active fire protection.

Tall buildings, in the event of fire, rely on three basic fire defence mechanisms, namely sprinkler systems, active fire fighting and passive fire protection to structural members, to overcome a collapse scenario. In the case of the twin towers, the severe fire conditions overcame the buildings fire defences considerably faster than expected. Due to the very high intensity of the fires, sprinklers, the first level of defence, were either ineffective or non-operational. Active fire fighting, the second level of defence could not be undertaken effectively since the fires were at higher floor levels (Glover 2002). Further, the impact of the planes had caused significant damage to fire proofing, the third level of defence, thus rendering the passive fire protection to structural members somewhat ineffective. Added to this was the status of structural members at impacted floors that were stressed to their full capacity. Therefore, the failure of the three basic fire defence mechanisms significantly contributed to the collapse of the towers.

4.6 Performance of Structural elements.

Steel loses its strength and stiffness when subjected to high temperatures. A typical steel structural member loses its load-carrying capacity (or about 50 percent of its original strength) at 538°C (1,000°F) when exposed to an ASTM E-119 standard fire (Kodur and Harmathy 2002). An unprotected steel member subjected to an ASTM E-119 standard heating environment is able to maintain its structural integrity for about 20 minutes. To limit this loss of strength and stiffness, external fire protection (fire proofing) is provided to the steel structural members to achieve required fire resistance ratings. Figure 4 illustrates the variation of strength and stiffness in steel as a function of temperature.

In the case of the twin towers, it should be noted that there was extensive damage to fire proofing and structural members before the onset of the fires. Further, the fire scenario was more severe than an ASTM E-119 standard fire that is often used as a bench mark for building fires. In addition, the fires were burning at multiple floors simultaneously. Also, the design of the twin towers considered only the impact forces of B707 jet aircraft and not the ensuing fires resulting from the jet fuel carried by such aircraft.

In the twin towers, as severe fires spread to additional floors and raised the temperatures of structural members over a period of many minutes, this induced additional stresses into the damaged structural frames, while simultaneously softening and weakening these frames. Further, the physical shock from the faster rise in temperatures and disruption of building elements undoubtedly removed some portion of the fire proofing from the floor deck, the bar joist trusses, the columns, the spandrel plates and other fire-proofed elements. The impact on the temperature of the structural members then became a function of the thermal properties of the fire proofing and the "heat sink" of each structural member.

One of the possible collapse mecahnism in twin towers is that the trusses, the weakest of the strucutral elements, expanded due to increasing temperatures and induced additional stresses on other structural elements, beyond their capacitiies, and also weakened the connections. The increasing high temperatures caused the floor slabs and lightweight steel assemblies to sag which produced an outward deflection of the columns and a stress overload from above, in addition to damaging the floor connections. This resulted in local collapse of floors and loss of lateral support to columns, over several stories, thus increasing the lateral unsupported length of the columns. This intiated significant buckling of columns which were already weakened by high intense fires and were in a highly stressed state.

Contrary to many early media reports, the steel did not melt. The melting point for steel varies with the alloy and is in the range of 1,500-1,600°C. Since the fire temperatures did not reach this value it is unlikely that there was any melting of steel. To date, only simplified analyses have been conducted to estimate the fire temperatures and the temperatures in the structural elements (Quintiere 2002) or to model the collapse of both towers (Bazant 2002). Detailed modeling of the fire, heat transfer to structural members and structural response under fire will provide the actual performance of structural elements during the WTC fires and will shed some insights into likely collapse mechanisms (Hernandez 2002).

5. Summary

The fire resistance issues played a major role in the collapse of the twin towers. The impact of aircraft caused massive damage to the structural system at impacted floors and left the structural members that withstood the impact in a highly-stressed state. The huge amount of jet fuel from the aircraft, though burned off with in the first few minutes, ignited office and aircraft contents, that resulted in massive fires. The fire intensity and heat output generated from these fires was much more severe than typical building fires; however, resulting fire temperatures was not significantly different from other building fires. The loss of fire defence mechanisms, including damaged fire proofing, further contributed to weakening the structural members. The intense heat from the fires attacked the structural system and, over a period of time, resulted in sufficient additional damage to the structural system to initiate a progressive sequence of failures that eventually culminated in the total collapse of both towers.

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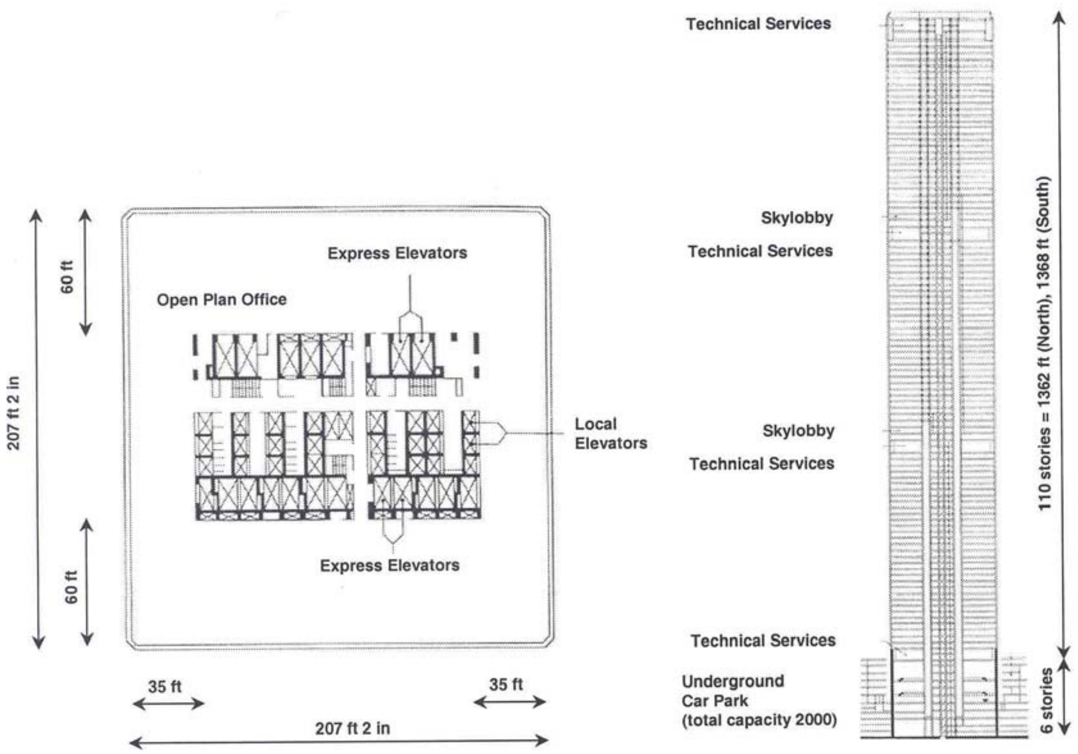

Figure 1 Typical floor layout and elevation in Twin Towers

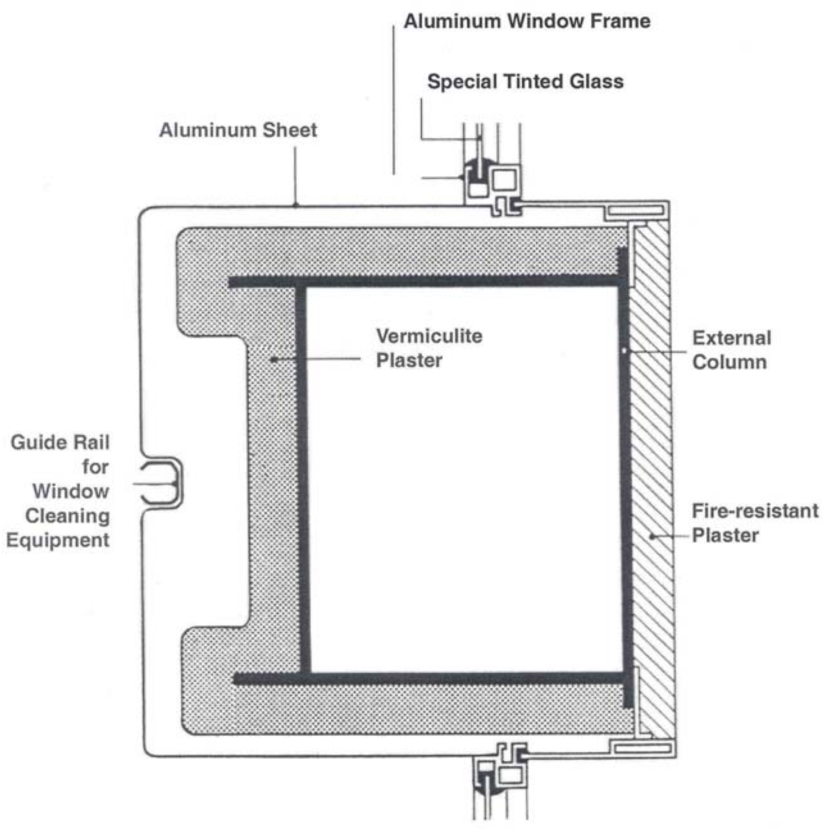

Figure 2 Fire Protection for typical Exterior Columns in Twin Towers

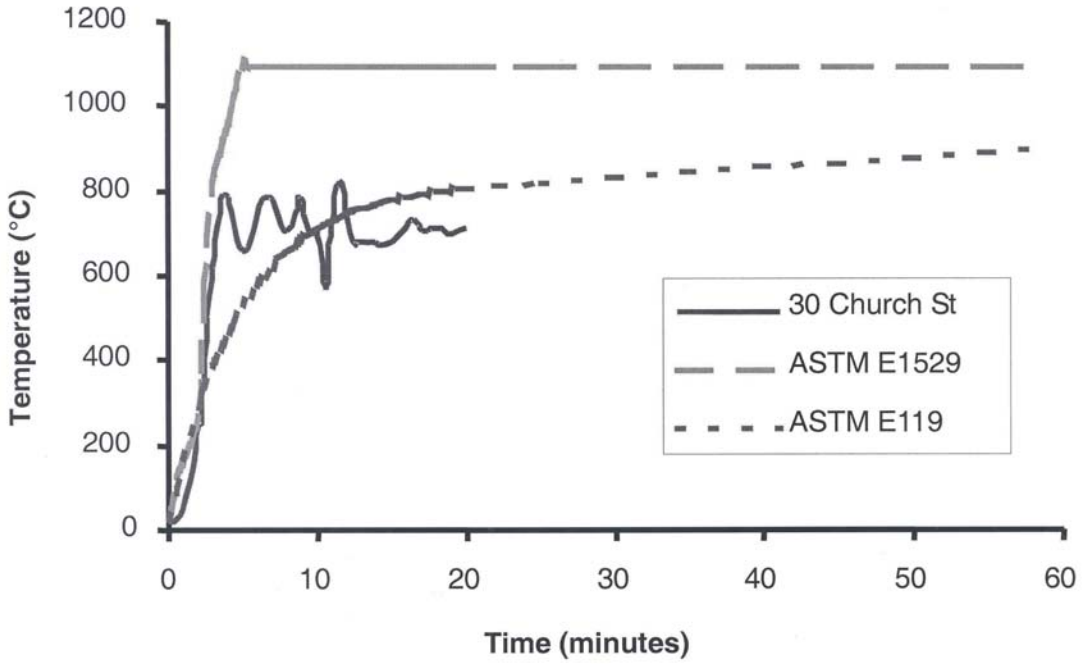

Figure 3 Time-Temperature curves from two standard tests and temperature measurements (DeCicco, et al., 1972) in the Hudson Terminal Building

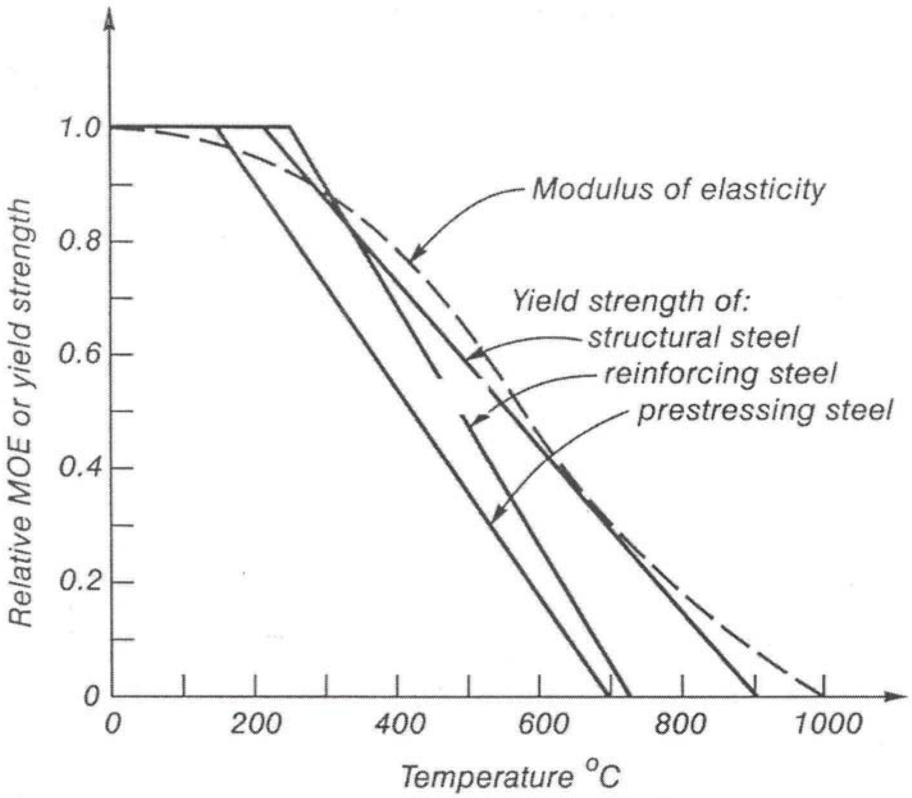

Figure 4 Variation of strength and Modulus of Elasticity of Structural Steels of with Temperature