Developing Strength Reduction Factor for Flexural Design of Reinforced Concrete Beams Exposed to Fire

By

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Abstract

Developing a moment reduction factor for design of the concrete beams exposed to fire

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Fire is a common hazard that may happen during the lifetime of concrete structures. Thus, it is one of the loads considered in building and tunnel design standards and codes. Dependency of the safety and structural integrity of a building to load-bearing elements such as beams requires the safe design of these elements. Flexural design of reinforced concrete (RC) beams under fire is critical. Typical load and resistance factor design (LRFD) of flexural member at ambient temperature deals with comparing the factored applied load with its capacity. Strength reduction factors are applied to the calculated nominal moment capacity to take into account several factors such as variations in material strength, poor workmanship, and uncertainty in determining the behavior of a member. However, the literature review conducted to-date revealed that no strength reduction factor has been developed for flexural design of RC beams subjected to fire. Current codes are confined to the calculation of the adequacy of the clear cover protection in concrete flexural members based on the ASTM E119 (2019) fire exposure (ACI 216, 2014). The proposed study aims to bridge this knowledge gap and develop a strength reduction factor for flexural design of RC beams at elevated temperature. Previous methods of design of RC beams show an absence of a factor that can assure safety in fire circumstances. Inadequate anticipated capacity can lead to the failure of RC members due to the loss of integrity and strength as a result of exposure to fire. The proposed research envisions to develop a strength reduction factor for flexural design RC beams subjected to fire/elevated temperature.

In order to drive this reduction factor, Parametric studies, in this case, reliability analysis utilized to develop an expression to evaluate the reduction factor for flexure design of the beam exposed to fire.

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1. Introduction

1.1. Background

Design of all structures comprises two important considerations, design for loads and hazards. Most of the buildings and structures are designed to last for several decades while they can function well. During the predicted lifetime of structures, different hazards such as earthquakes, fire, etc. can happen. These hazards can cause partial or complete damage to the building or other kinds of structures and they may even cause failure or collapse and as a result of this imperfection, the safety of the inhabitants can be put at risk. Therefore, the design of the buildings and other structures should be reliable and safe. Fire is one of the hazards that can happen during the lifetime of the buildings and endanger the safety of its inhabitants.

Fire hazards in buildings can be defined as the potential of accidental or intentional fire to threaten life, structural, and property safety in a building.

1.2. Problem statement

There is no generalized and user-friendly method that includes most of the factors for fire design like any other designs such as flexure, shear, and torsion design of structures.

1.3. Objectives

Since 1986 LRFD design became a method for design of the structures. Since then researchers and committees used this method for designing the structures for different types of loadings such as flexure, shear, and torsion. Even though the design of the structures for fire is an important requirement, but there is no comprehensive and user-friendly method for fire design based on the LRFD method.

Even though reinforce concrete (RC) structural members generally exhibit good fire resistance,

However, under fire exposure, RC members experience loss of strength and stiffness as a result of increased temperatures in reinforcing steel and concrete. Depends on the severity and duration of the fire exposure loss of capacity in RC structural members differs, so as residual capacity.

Since now residual capacity has been used for the decision of retrofitting or demolishing the structures. While the residual capacity can be used for the development of a factor that can be used for fire design based on the LRFD method.

The main goal of this study is to expand the borders of the LRFD method for the design of hazards such as fire.

This research comprises two different parts, numerical study and reliability analysis.

The first part involved an analysis of the experimental data and parametric study. The used experimental data were based on the ASTM-E119 and ISO 834.2012. ABAQUS software has been used for the numerical study phase.

The second part was the reliability analysis. A flowchart and a program have been developed based on using Monte Carlo simulation. The program has been written in Python language.

The research was conducted with the main objective of developing a strength reduction factor for flexural design of RC beams at elevated temperature.

1.4. Organization of thesis

This thesis is organized into five chapters. The content of each chapter describes as follows:

Chapter 2- Literature Review

In this chapter, a review of previously performed experimental and numerical studies on … has been presented.

Chapter 3- Numerical Study

This chapter discusses the numerical modeling and parametric study performed to study the effect of different parameters on the tested samples.

Chapter 4- Reliability Analysis

In this chapter statistical analysis of the research in the form of reliability analysis based on the Monte Carlo simulation has been presented.

Chapter 5- Summary, Conclusion and, Recommendation

The summary of the research is presented. The conclusions resulted from the numerical modeling, parametric study, and reliability analysis are delineated. Finally, Recommendations that need further research are proposed.

2. Chapter 2

Literature Review

2.1. Fire hazards in concrete buildings

Buildings are important structures that serve many vital needs for humans. Most of the buildings are built in a way that they can have serviceability for many years. History shows that buildings often experience natural or manmade hazards such as earthquakes, tsunamis, fire, etc. during their lifetime which can endanger the safety of the building inhabitants and their property.

The possibility of haphazard or deliberate fire that can threaten the life of inhabitants, structural and property safety can be considered as a Fire hazard in buildings. In recent years fire hazards became a serious concern because of the severity and diversity of fires. The cause of more than one million fire deaths in the past two decades and the second number of deaths in the USA shows the importance of fire safety in buildings. In 1988 the council of European communities considered fire safety as one of the six essential requirements that must be satisfied in construction.

A set of prudence and actions regarding avoiding or prevention fire incidences and controlling the increment of deliberate or unintentional fires is considered as fire safety. Provisions in the existing building codes provide fire safety in the buildings. Most of the codes are using perspective based approaches are not considering many features that happen in an actual fire, therefore, they can not simulate conditions of a real fire.

Fire is a considerable threat to life, structure, property, and the environment. It can threaten life during both initial and fully developed stages. In the initial stages, toxic gasses such as carbon monoxide, hydrogen cyanide, and phosgene gas produced by ignition are noxious, and inhaling them is extremely lethal. NFPA (2018) reported that more fire death happens because of toxic gasses than combustion alone. Situation of fully developed fire bring definite death for human. By burning off the materials oxygen level drops to the point that humans can not withstand it. In the fully developed stage, fire can be more than that will follow the loss of strength (Kodur-2014), which can lead to intolerance of load-bearing members to carry applied loads, in some cases, it can also cause a collapse of the building.

Based on the US fire administration there were 1,318,500 fire cases in 2018 which had a negative rate of -2.5% in comparison with 2009. The number of death caused by the fire was 3655 in 2018 with an increasing rate of 20.5% since 2009 and caused a loss of 25.6 billion dollars with an increasing rate of 90.6% from 2009.

Based on a U.S. fire administration report in 2018 by general property type classification 30% of fires occur in residential buildings. Therefore, the importance of a safe design is more substantial.

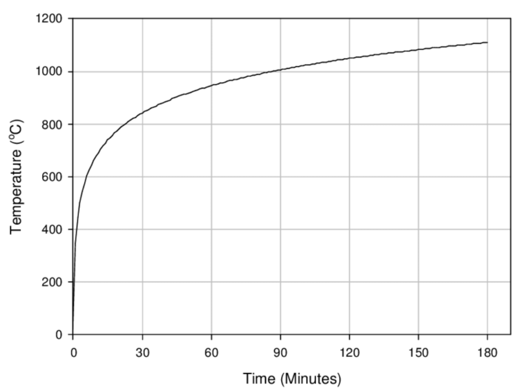
Prevention of fire incidence is the first method to deal with fire situations. Since fire is a supervenient phenomenon, perennial avoidance of it is impossible. Hence, the impacts of fire including the fire situation itself, people, and their property that is exposed to fire should be controlled. Evacuating people from the building by a safe fire escape path is a common way to manage people. However, this method is not applicable for high rise buildings. In high rise buildings, there are safe refuge on certain building levels, so that firefighters evacuate those certain levels. Controlling combustible materials and using different fire protection systems installed in the building is the general procedure of managing fire. Structural stability is the last line of defense of the building toward the fire. The structural stability is very important and crucial, the more a building is stable during a fire, the more the firefighters have time to rescue lives from the burning building. Building codes specify provisions to avoid fire incidence and control its impacts. For the design and assessment of the fire resistance of structural members, there are guidelines in building codes. For the design of a building for fire conditions, codes determine how members should function in a fire situation. They also determine limitations for fuel density and desirable fire ratings of members, advice on material type and member size limitations that depend on the type of the building, because different building occupancy such as hospitals, residential, etc. have different fire ratings.

Stability (R), integrity (E), and insulation (I) are three main fire safety factors that a building code used to evaluate the fire safety of a structural member. The procedure of fire resistance evaluation can be performed by these three fire safety factors (Buchanan and Abu, 2017). By corresponding member features to fire safety factors by utilization of standard fire tests data, evaluation of fire resistance is perspective approach can be performed. While in advance analysis procedure parametric fire curves provided by codes are used with constant fire safety factors (Eurocode-2,2004).

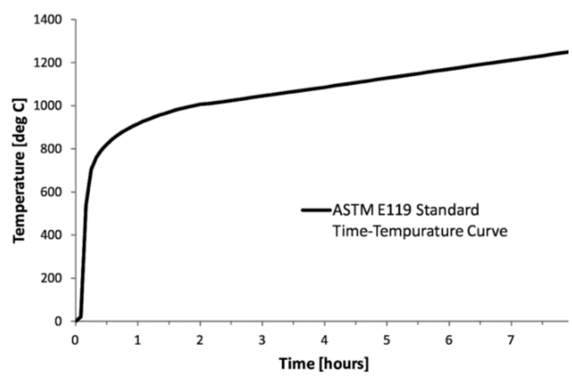
There are two kinds of fire safety provisions in the buildings, active and passive protection systems. Structural design of members in order to satisfy fire safety is considered a passive fire safety provision. In the developed stage of fire thermal expansion and material degradation happens which are the result of temperature rising. In this phase, assuring structural safety stability and bound the propagation of fire is the primary goal of a passive protection system. Safe fire and evacuation operations and decrement of property detriments are the result of a passive fire protection system.

Abundance of combustible materials leads to shortening the initial stage of fire and the early start of the developed stage of fire, on one hand, new material and architecture on the other hand makes fire safety very challenging. Modern fire hazard challenges haven't been covered desirably in the present fire protection system criteria.

Building codes such as ISO 834-1, 2012, and ASTM E119-2019, 2019 are using standard fire curve for characterizing structural fire, these fire curves have been shown in Figure 2.1. Structural fires do not demonstrate actual fires that happen in reality because they are very conservative. They also do not account for openings, oncoming burning, and combustible materials. However, they have a solemn effect on the fire temperature in the developed stage.



(a)



(b)

Figure 2-1.Standard Fire Curve

The method of the guidelines that codes are using to calculate fire resistance of members either structural or nonstructural is through calculating resistance of an acceptable structural member in standard fire at service load with simply supported restrains and simplified failure criterion and expand it to other members with different features such as dimension, concrete cover, aggregate type, reinforcement, etc.

From 2012 to 2016, failure of smoke alarm operation leads to 25700 home fires and consequently 440 death and 1440 injuries each year (Ahrens, 2019). A review by (Frank et al., 2015) showed that the efficiency of the general sprinkler system is ranging from 70.1 to 99.5 percent. Therefore, active fire protection systems are not completely reliable.

In current design codes, fire safety is considered as a further restriction, Maluk et al. (2017) researched merging fire safety with building design procedure.

An iterative decisive method was presented by Gehandler in 2017, his effort aimed to change the linear decision-based fire safety design. This research and other studies could not come with a general method to assuage fire hazards. Location, building type have an effect on most fire safety methods (Chien and Wu, 2008; Chen et al., 2012; Cowlard et al., 2013; Navitas, 2014; Nimlyat et al., 2017); therefore, their result can't cover all case around the world.

in 2012 Coile, CAspeele and Taerwe worked on the Global resistance factor for concrete slabs exposed to fire.

2.2. Residual capacity of concrete structures after fire exposure

The total collapse of a building is not common when the structure is subjected to fire (Beitel and Iwankiw, 2005). Since RC structures have low thermal conductivity, high thermal capacity, and slower degradation of mechanical properties total collapse is even less possible (Tovey and Crook,1986; Kodur, 2014; Kodur, 2017). Even though reinforced concrete (RC) usually shows good resistance toward fire, but fire exposure causes strength loss in RC members. In the situations where they experience high-temperature structural exteriority will happen to RC members. After fire exposure, there is some capacity left in the member known as residual capacity.

Temperature-dependent properties and degradation of materials, fire duration and severity, load levels, and conditions of restrains influence the residual capacity of an RC member. It also depends on the temperature history of the member (Kodur and Agrawal, 2015; Kodur and Agrawal, 2016; Kodur and Phan, 2007). Many of these parameters such as load level, boundary conditions, post-fire residual deformations, and have not been considered in Most of the residual capacity evaluation procedures (Bai and Wang, 2011; Kodur et al, 2013; Kodur et al, 2010, Kodur and Agrawal, 2016).

In 2015 Kodur and Agrawal came up with a method for evaluation of residual capacity of RC beam exposed to fire. Their method consists of three stages; capacity evaluation using finite element modeling analysis at ambient temperature (stage 1), thermo-mechanical analysis with a specific percentage of the beam ultimate capacity when the beam is subjected to fire (stage 2) and evaluation of capacity after fire exposure after cooling down (stage 3).

The stress-strain curves for rebars and concrete within room temperature analysis, thermo-mechanical analysis heating stage and cooling phases after the beam subjected to fire, and residual stage of analysis are depicted in Figure 2.2 and Figure 2.3 respectively (Kodur and Agrawal, 2015).

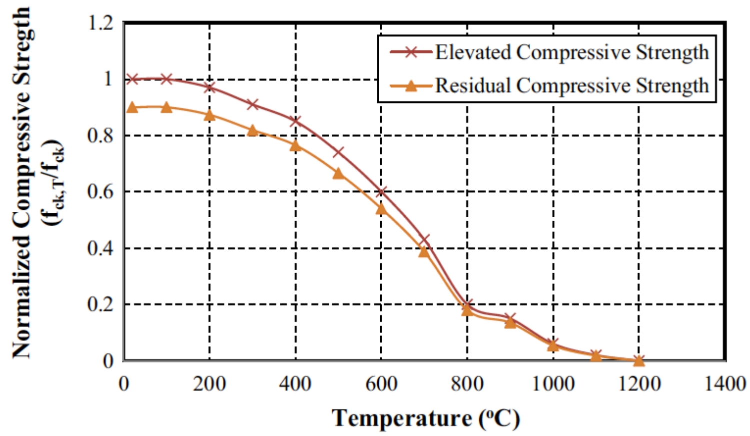


Figure 2-2. Normalized compressive strength of concrete with maximum exposure

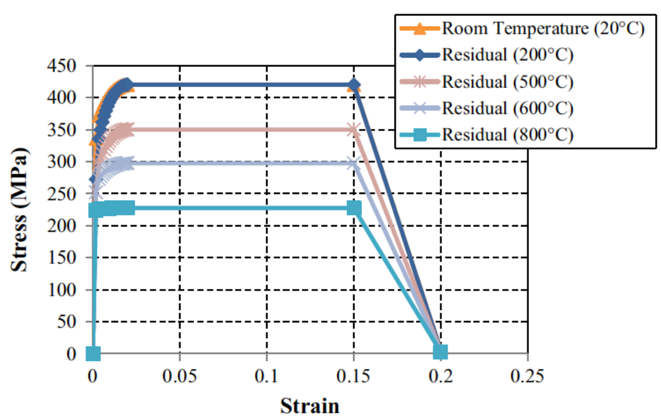


Figure 2-3. Residual stress–strain curves for reinforcing steel having yield strength of 420 MPa.

2.3. Reliability analysis of a reinforced concrete exposed to fire

The fire-resistance rating of a structural member can be specified either by a fire endurance test based on ASTM E119 (ASTM 2019) or calculation. Application of these methods is limited since fire endurance test results exist for similar structures [American Concrete Institute (ACI) 1989,2007; ASCE 2006]. A fire rating is not a comprehensive measure in case of safety since it does not consider failure probability, and the reliability of RC structures exposed to fire loads. In the LRFD method by load and resistance factors have been developed in various load combinations that can assure a solid safety level for structural members. However, fire resistance does not have the countability that members have a solid safety level (Meacham 1997; Kruppa 2000; Kodur and Dwaikat 2011).

Furthermore, different guidelines consider different load combinations during fire exposure, which depict that there is no principled method for fire in the standard codes for the design of the RC member.

Recently some studies have been conducted on the probabilistic analysis of structures exposed in fire situations. These comprise the studies of Beck (1985) on the reliability of structural steel members exposed to fires; Shetty et al. (1998) that used reliability analysis for the evaluation of the fire safety of offshore structures and Teixeira and Guedes Soares (2006), with estimation of load-bearing steel plates subjected to localized heat loads using the reliability. Practical design load combinations in fire design situations have been presented by Ellingwood (2005). Some of the studies have put failure probabilities of RC structural elements exposed to fire into account. These include Ellingwood and Shaver(1977), who have considered Weibull distribution for resistance and deterministic loads. Courge et al. (2004) worked on the reliability of a concrete tunnel exposed to fire, also Sidibe et al. (2000) and Wang (2008) conducted a study on the fire reliability of RC columns. preliminary estimation of the reliability of a fire-exposed RC beam has been conducted by Jensen et al. (2010). But still, there is no principled method for evaluation of the reliability of RC beams exposed to fire in current codes.

2.4. Load and Resistance Factored Design for structures exposed to fire

Recently European Coal and Steel Community (ECSC) has done research intending to find load factors in fire situations applying simplified assumptions. They have considered different fire load scenarios and active fire protection system influence.

In 2011 Iqbal and Harichandran developed fire load factors. The statistical parameters such as the mean, coefficient of variation (COV), and distributions of design parameters have been obtained, afterward, an appropriate performance function for the structural member has been chosen. Specifying model error and target reliability was the next step and the last step was calculation of the fire load factor through reliability analysis. They have concluded that fire load factors are not the same for different situations and it also depends on the presence of active fire protection systems in a building.

2.5. Material properties at elevated temperature

Reinforced concrete is a compound material. Hence, the properties of each component of it plays an important role in the behavior of RC member in the fire situation. There are four categories for material properties for each material including compound material like reinforced concrete. These three categories are mechanical, thermal, deformation, and material-specific properties. The first two categories define the thermal and mechanical reaction of the member. Each one of these categories comparts of different properties.

The mechanical properties category comprises compressive and tensile strength, modulus of elasticity, and stress-strain response. This category plays a key role in strength loss and stiffness decadence.

The thermal properties category includes specific heat, thermal conductivity, thermal diffusivity, and mass loss. Specific heat is the required heat that increases the temperature of the material by one degree. Thermal conductivity is the degree to which a material conducts heat. Thermal diffusivity is the division of thermal conductivity by density and specific heat when the pressure is constant, it defines how much heat has been transferred from the surface of the member that has been exposed to fire to the inner portion.

Deformation properties category includes thermal expansion, transient strain, and concrete and reinforcement concrete creep. When the temperature changes, the material tends to change its dimension, this property of the material is known as thermal expansion. The thermal incongruity of the aggregates with the cement paste causes transient strain in concrete when it’s heated for the first time. This property is intrinsic and it’s not time-dependent (Purkiss, 2007).

After performing several high-temperature material tests such properties are determined. Two reliable sources for high-temperature material properties are ASCE Manual of Practice No. 78 (1992) and Eurocode 2 (2002) are the two widely accepted sources for high-temperature material properties.

In the following subsections, these properties for concrete and reinforcement steel has been presented.

2.5.1. Concrete

Concrete is a common material and that has diverse formations. Its properties such as thermal, mechanical, and deformation pertain to its compound material combination and compressive strength of it.

The thermal properties of concrete depends on the aggregate type. They divide into two main categories, siliceous and carbonate aggregate. There is another classification for concrete type based on its strength. Concrete with a strength of 20 to 50 MPa (2.9 to 7.25 ksi) are normal strength concrete (NSC), and those with a strength of 50 to 120 MPa (7.25 to 17.4 ksi) are high strength concrete (HSC) (Kodur, 2014).

Thermal Properties of Concrete

Factors of moisture content and aggregate type of concrete influence the thermal conductivity of concrete. These two factors plus concrete density can influx specific heat (Phan 1996; Harmathy et al. 1973; Kodur and Sultan 1998).

The published experimental data (Shin et al. 2002; Harmathy and Allen 1973; Harmathy 1970; Kodur 1998; Lie and Kodur 1996; Harada 1972) and empirical relationship (EC-2 2004 and ASCE 1992) on the alteration of thermal conductivity of NSC with temperature has been combined by Khalid (2012), Figure 2-4. The results of different tests have been shown in the shaded area. Significant differences due to moisture amount, aggregate type, test condition, and evaluation methods can be precepted in the figure. Temperature and thermal conductivity have an indirect relationship, so a rise in the temperature results in a reduction of thermal conductivity which can be a consequence of decrement in moisture with increment in temperature (Bazant 1996). Aggregate type has an effect on the ASCE model thermal conductivity model, while in the Eurocode model an upper and a lower bound is presented. fire tests on different types of concrete structures made the lower bound, therefore it has more precise outcomes. while The upper bound is a result of tests on steel/composite structures (Hatinger 2012).

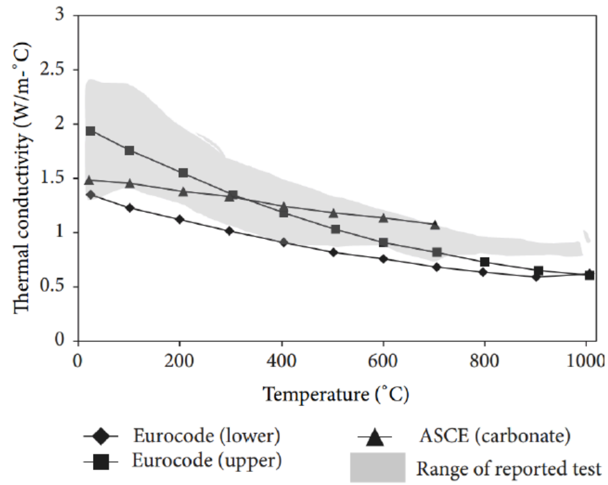


Figure 2-4. Variation of thermal conductivity of NSC with temperature (Kodur 2014)

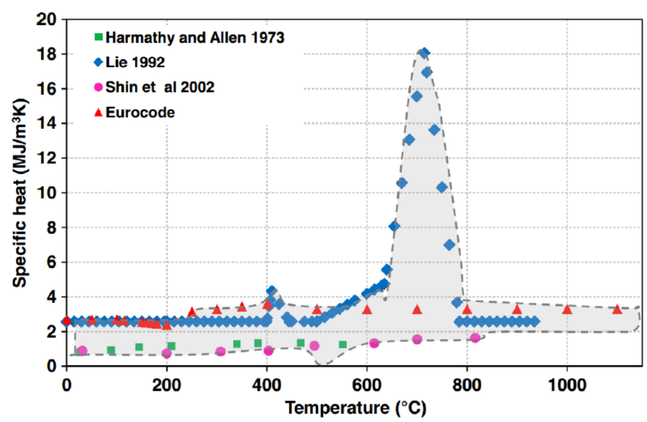


Figure 2-5. Variation of specific heat of NSC with temperature (Kodur and Khalid 2011)

low water-to-cement ratio and use of different binders in HSC leads to higher thermal conductivity in HSC (Kodur and Khalid,2011).

The published experimental data (Harmathy and Allen 1973; Lie 1992; Shin et al. 2002; Eurocode 2004) on the NSC specific heat variation with temperature has been combined by Kodur and Khalid (2011) as shown in Figure 2-5. Significant change as a result of different moisture amounts, aggregate type, test condition, and evaluation methods in the thermal conductivity and specific heat data is indicated (Kodur and Sultan 1998; Harmathy and Allen 1973; Eurocode 2004;

ASCE 1992). The specific heat capacity remains the same until then increases and again it remains the same until. Due to dolomite decomposition in carbonate aggregate, there is a peak in heat capacity in the range of to. In 2003 Kodur and Sultan reported that from to specific heat of HSC is slightly lower than NSC.

Mechanical Properties of Concrete

Tensile strength, compressive strength, modulus of elasticity, and stress-stress relationship are Mechanical properties of concrete. At high-temperature no standard has been defined for specimen size like room temperature property evaluations, therefore at high-temperature mechanical properties evaluation tests a wide range of specimen sizes and loading conditions is being tested (Khalid 2012).

Variation of normalized compressive strength of NSC and HSC with temperature changes has been shown in Figure 2-6 and Figure 2-7. Because of the penetrable feature slight trace of change in compressive strength of NSC due to the Rise of temperature can be seen in figure 2-5. However, because of the microstructure of HSC that makes it extremely impenetrable, compressive strength decreases faster with a rise in temperature as shown in Figure 2-7. the difference in heating or loading rates, specimen size and curing, moisture content, age of the specimen, and presence of admixture are reasons for the difference between results of different tests (Kodur 2014).

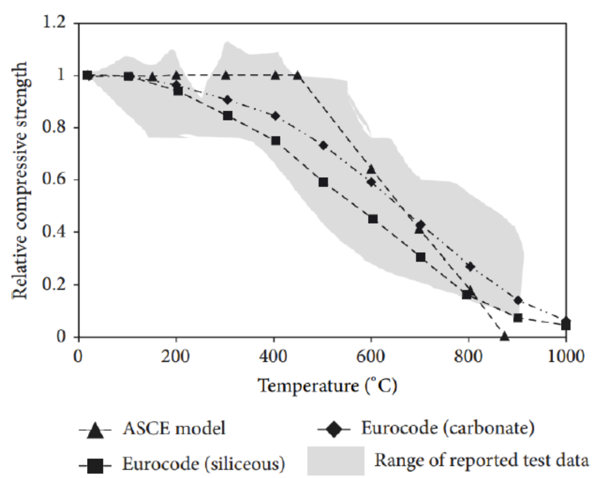


Figure 2-6. Relative variation of compressive strength of NSC as a function of temperature (Kodur 2014)

The respective changes in the tensile strength of HSC and NSC with temperature have been shown in Figure 2-8 (Behond and Ghandehari 2009; Carette et al. 1982; Felicetti et al. 1996; EC-2 2004). Decrement of the tensile strength of concrete with an increment of temperature in both HSC and NSC is observed. NSC loses about 20 percent of its tensile strength until. Above this temperature because of micro- Cracks as a consequence of thermal damage, it decreases promptly (Kodur 2014). The modulus of elasticity of HSC and NSC both has reductional rate with increment

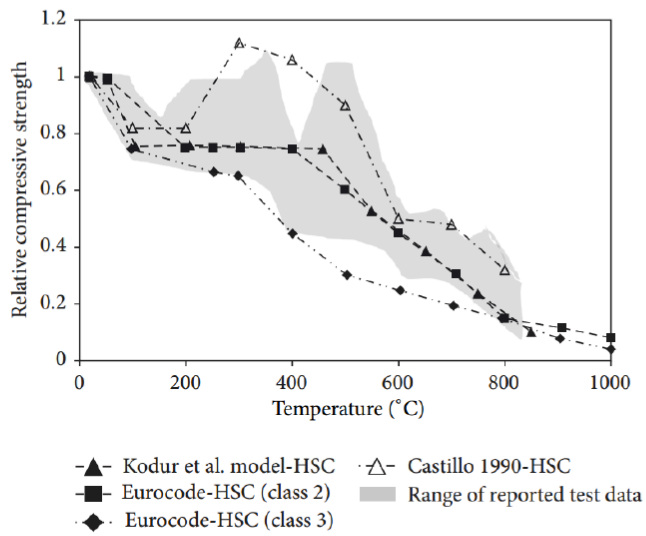


Figure 2-7. Relative variations of compressive strength of HSC as a function of temperature (Kodur 2014)

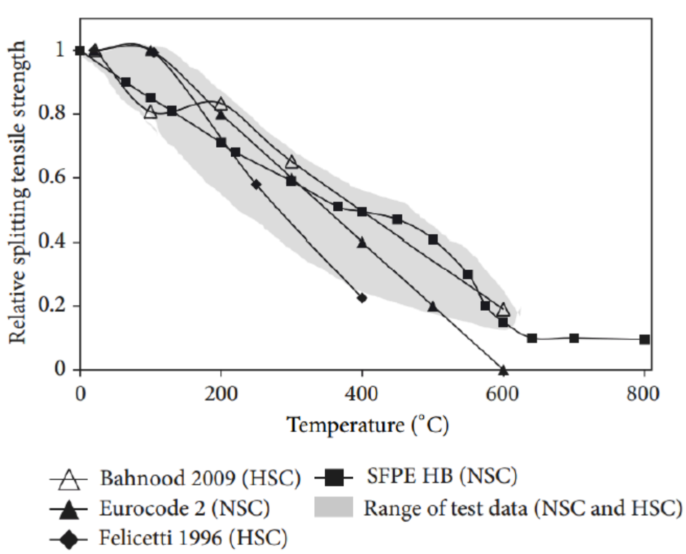


Figure 2-8. Relative variations of tensile strength of HSC as a function of temperature (Kodur 2014)

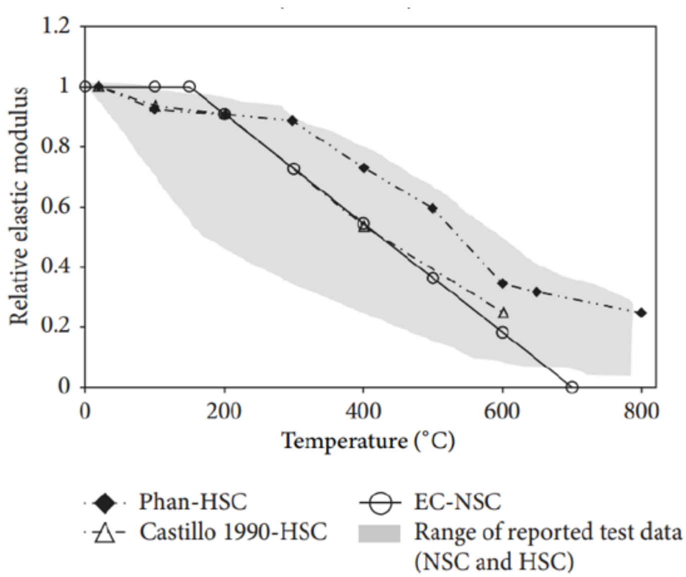


Figure 2-9. Relative variations of modulus of elasticity of concrete as a function of temperature (Kodur 2014)

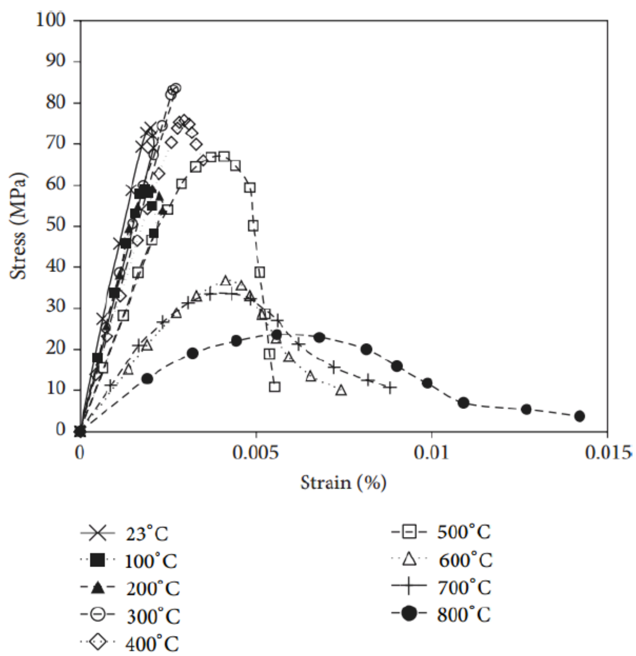


Figure 2-10. Stress-strain diagram of NSC at elevated temperatures (Kodur 2014)

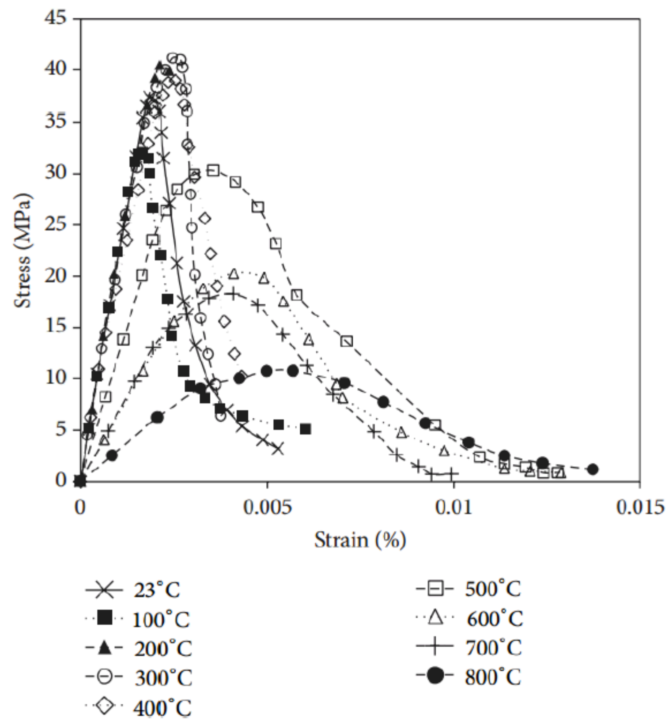


Figure 2-11. Stress-strain diagram of HSC at elevated temperatures (Kodur 2014)

In temperature, they have been shown in Figure 2-9 (Castillo and Durrani, 1990; Phan, 1996; EC-2 2004).

In Figure 2-10 and Figure 2-11, The stress-strain diagram of NSC and HSC has been shown respectively. it can be seen that with increment in temperature the peak stress decreases. However, ultimate strain and ductility have direct relation with temperature. unlike NSC, the reaction of HSC exhibited a brittle in all temperatures.

Deformation Properties of Concrete

Aggregate type, chemical compound, and physical and chemical responses of concrete in temperature rising leads to thermal expansion, creep, and transient strains that have been categorized as deformation properties of concrete.

Figure 2-12 shows how the coefficient of thermal expansion of NSC varies with temperature (ASCE 1992; EC-2 2004; Kodur et al. 2008; Raut 2011). The coefficient of thermal expansion of concrete with carbonate aggregate is more than siliceous aggregate (EC-2 provision,2004). Plastic deformation of materials under constant stress level for a period of time is creeping, mostly when the deformation that has been produced from a stress less than the yielding point of the material is permanent. Since variation of moisture content is high at elevated temperature, creep strain is considerable. Creep depend on several variables such as temperature, level of stress, time, loading, and concrete mix design (Dwaikat 2009).

The cement paste and aggregates have different thermal expansion. This difference added with the influence of high temperature on the amount of moisture and chemical combination of concrete result in internal stresses and microcracking. internal stresses and microcracking leads to transient strain in concrete (Schneider,1988). Transient strain only happens in concrete during its first time heating (Khoury 2000).

After evaluation of total strain by subtracting mechanical strain as well as thermal strain, transient and creep strain are can be evaluated together. It's because there is no specific test for transient strain evaluation. In ASCE 1992 and Eurocode (2004)

guidelines there is no direct relationship for both transient strain and transient creep strain.

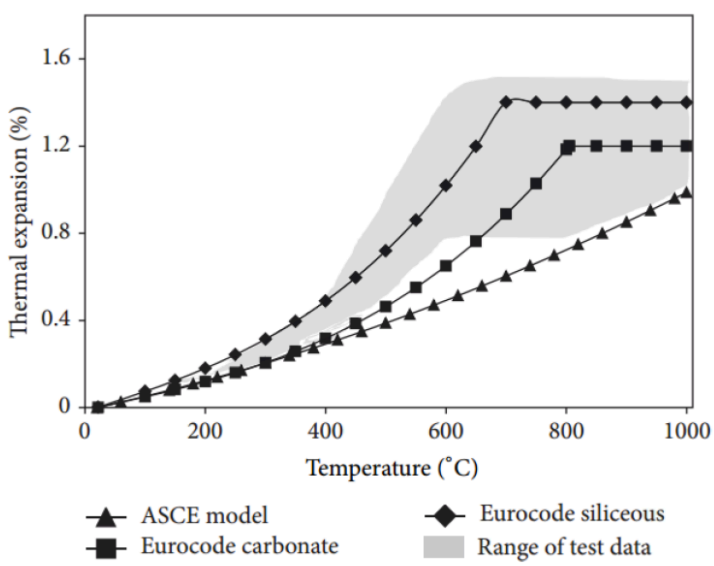


Figure 2-12. Variation of coefficient of thermal expansion of NSC with temperature

2.5.2. Steel reinforcements

Each category of steel properties including thermal, mechanical, and deformation influence the response of reinforcement in high temperature. The review of these properties is stated below.

Thermal Properties

Steel has high thermal conductivity and low specific heat capacity. Even though there are several factors such as metallurgical compound, reinforcement type, and temperature that influence the thermal properties of steel, but in an elevated temperature, the only significant factor is temperature itself (Hatinger 2012). Since the area of the mild steel reinforcement compared to the concrete area is not considerable, therefore, steel effect on the distribution of temperature in the concrete cross-section is negligible. As it has been depicted in Figure 2-13 and Figure 2-14 based on Eurocode (2005) The thermal conductivity has a linear decreasing variation with increasing temperature until 800°C and after that remains the same. Gradual variation of the specific heat capacity for most of the temperatures can be seen. Except for the pinnacle that it shows at a temperature range between 700-800°C because of the steel crystal structural phase change (Wang et al. 2013.)

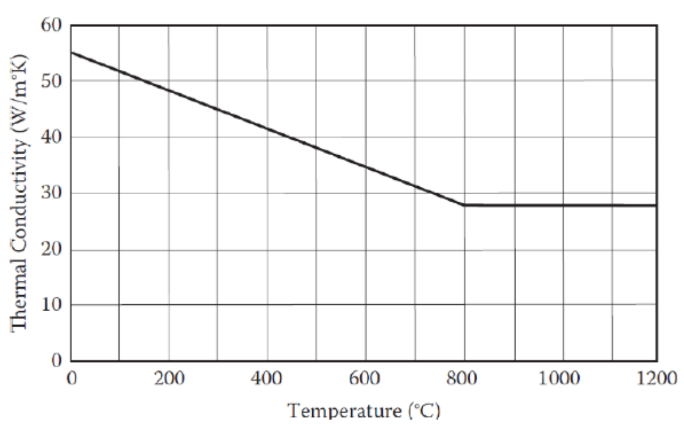


Figure 2-13. Variation of thermal conductivity of steel with temperature (Eurocode 3, 2005)

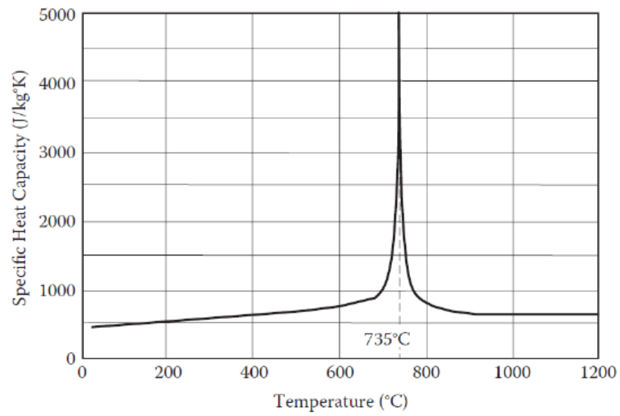


Figure 2-14. Variation of specific heat capacity of steel with temperature (Eurocode 3, 2005)

Mechanical Properties

yield strength, ultimate strength, modulus of elasticity, and stress-strain relationship are the mechanical properties of steel that can affect the strength and stiffness of reinforcement. Rate of heating and strain, temperature, and reinforcement type influence these categories of properties.

stress-strain curve change at different temperatures has been presented in Figure 2-15. As can be seen from the figures, the strength and stiffness of reinforcement have a decremental change with temperature.

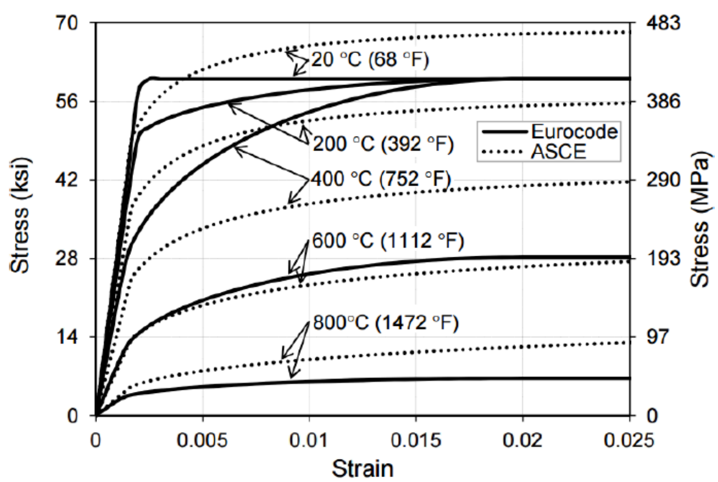


Figure 2-15. Variation of specific heat capacity of steel with temperature (Eurocode 3, 2005)

The ultimate strength variation of prestressing steel and mild reinforcement with temperature has been shown in Figure 2-16 based on Eurocode-3 (2004), ASCE (1992), and PCI (2004). In Eurocode-3 and PCI model an S-shaped ultimate strength decreasing curve can be observed.

Eurocode states that strength loss of prestressing steels begins at 100°C, unlike mild reinforcements that begin at 400°C. However, mild reinforcing steel in the ASCE model begins to lose its strength linearly immediately up to 20 % of its strength at 900°C, and then complete degradation of it happens at 1000°C.

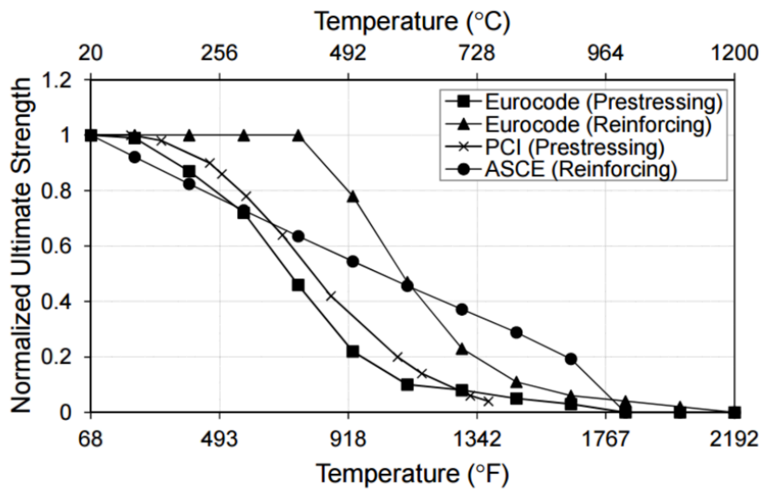


Figure 2-16. Variation of ultimate strength with temperature for mild reinforcement and prestressing steel (Eurocode 3, 2005; ASCE 1992and PCI 2004)

Yield strength change of prestressing steel and mild reinforcement in relation to temperature has been presented in Figure 2-17 as per Eurocode-3 (2004) and ASCE (1992) guidelines. Decrement of the yield strength with increment in temperature can be seen from all of the curves.

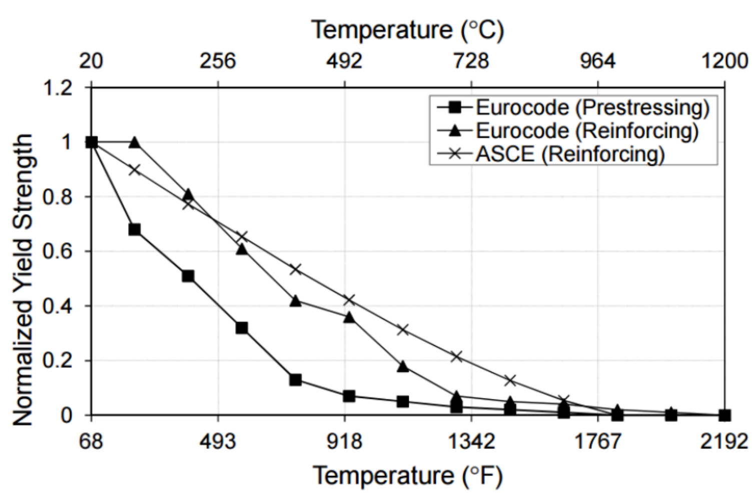


Figure 2-17. Variation of ultimate strength with temperature for mild reinforcement and prestressing steel (Eurocode 3, 2005; ASCE 1992and PCI 2004)

Elasticity modulus change of prestressing steel and mild reinforcement with regarding to temperature have been shown in Figures 2-18 and 2-19 depicts the variation of as per the provision of Eurocode-3 (2004) and ASCE (1992). In all of the models, the modulus of elasticity has decreased with an increase in temperature.

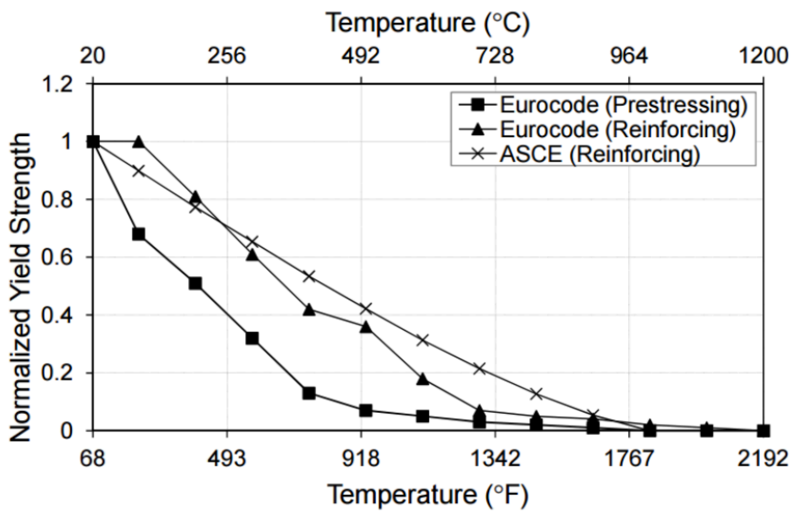


Figure 2-18. Variation of mild reinforcement and prestressing steel yield strength with temperature (Eurocode 3, 2005; ASCE 1992and PCI 2004)

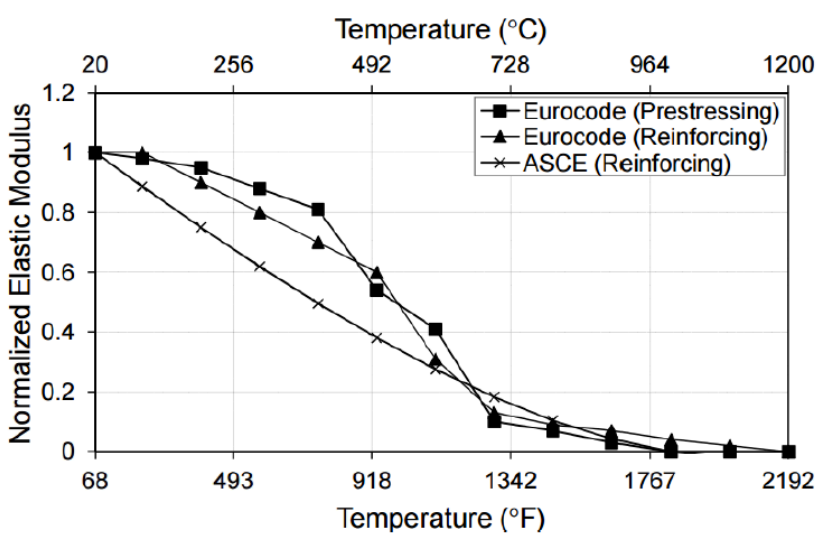


Figure 2-19. Variation of mild reinforcement and prestressing steel modulus of elasticity with temperature (Eurocode 3, 2005; ASCE 1992)

Deformation Properties

The variation of thermal elongation and creep strain with temperature that have been categorized as deformation properties of steel have been depicted in Figure 2-20 for prestressing steel and mild reinforcement (Eurocode 3, 2005; ASCE 1992). Linear increment of thermal strain with temperature rise can be observed from both models.

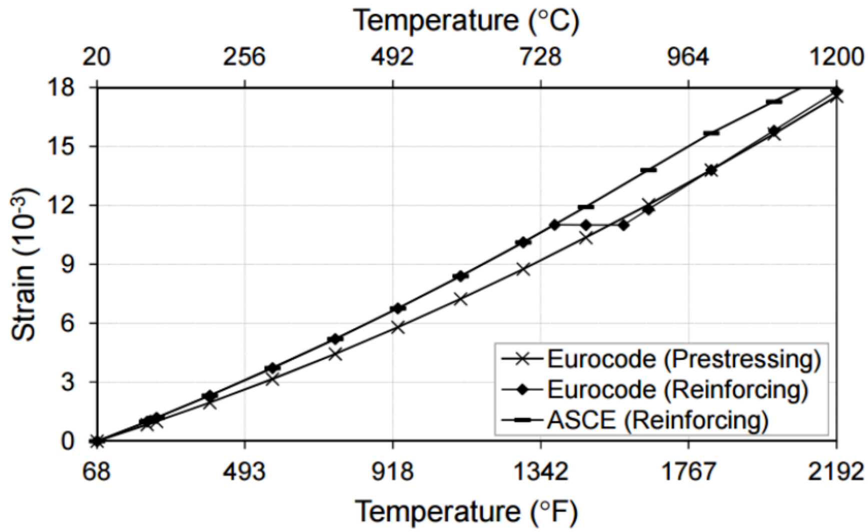


Figure 2-20. Variation of mild reinforcement and prestressing steel thermal elongation with temperature (Eurocode 3, 2005; ASCE 1992)

3. Chapter 3

Data analysis

3.1. Introduction

In order to develop a moment reduction factor for the design of the concrete beams exposed to fire

Experimental data is needed. These experiments are from different studies. In each of these studies several factors such as beam size, concrete compressive strength, fire duration, etc.

In the following sections, each of these experiments and their results have been presented.

3.2. Experimental data

3.2.1. Experiment 1

This experiment has been performed by Eummi Ryu, Yeongsoo Shin, and Heesun Kim, 2018.

In this experiment, twelve RC beams were constructed with normal strength. Variables of these beams are time, beam size, loading, which is related to duration of fire exposure, cross-section dimensions, initial load level. All of these variables have been listed in Table 3-1. The width, depth, and length of the RC beams are 250 mm × 400 mm × 5000 mm, and 300 mm × 500 mm × 5000 mm, and 350 mm × 650 mm × 5000 mm, as is shown in Figure 3.1. The ratio of the reinforcement is the same for all of the beams, therefore respecting the area of the cross-section the number of rebars variated. The reinforcement arrangement for the rebars in the S series is three steel bars with a diameter of 19 mm, in the M series five steel bars with the same steel bar, and in the L series seven steel rebars with the same diameters as well. In order to avoid shear failure stirrups with a diameter of 10 mm have been provided, as illustrated in Figure 3.1. Curing time was the same for all of the beams and it was four months.

The average of the compressive strength of the concrete after 28 days is 25.08 MPa, and the average tensile strength is 2.98 MPa. The yield strength and modulus of elasticity for the reinforcements including rebars and stirrups are 448 MPa and 205 GPa respectively.

according to ISO 834 standard time-temperature curve, three surfaces of the beam have been exposed to fire. The specimens are left for 7 days after the fire test. In order to measure residual capacity, all beams are subjected to the four-point bending test until the beam shows failure, as shown in Fig. 3.2.

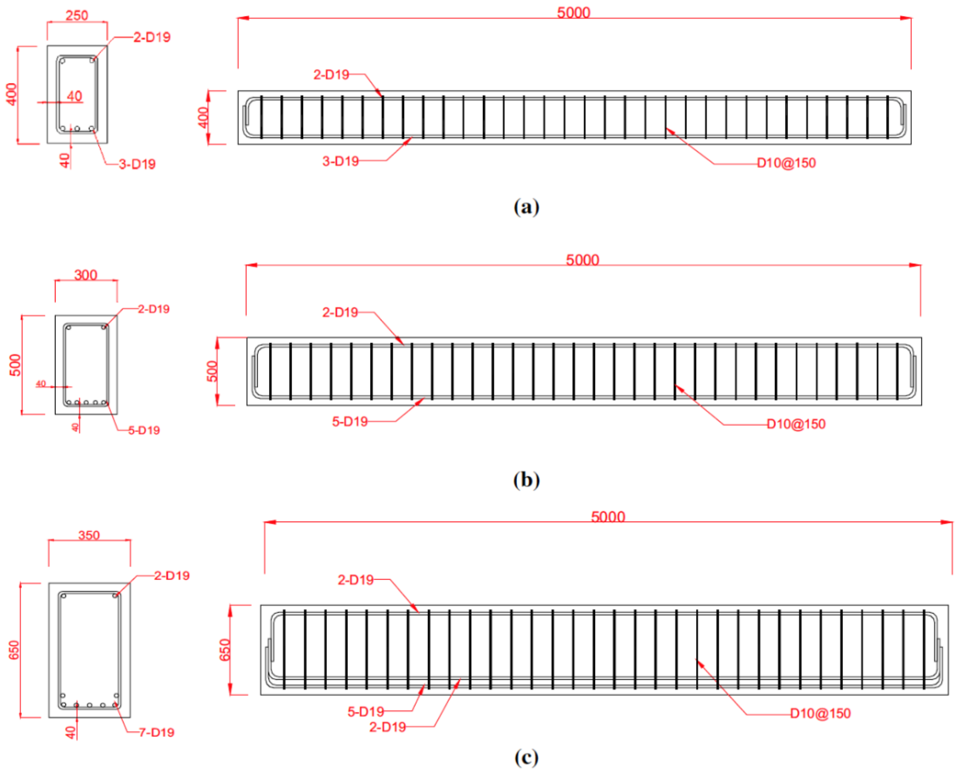


Figure 3-1. Details of the specimens (unit mm). a S series, b M series, and C L series

Table 3-1. LIST OF Specimens

Specimen	Size (Width × Depth × Length)	Fire exposure duration
CONT	250 mm × 400 mm × 5000 mm	-
P1-60	(S series)	60
P1-90		90
P1-120		120
P2-60		60
P2-120		120
P3-60		60

P3-120		120
MCONT	300 mm × 500 mm × 5000 mm	60
MP1-60	(M series)	120
LCONT	350 mm × 650 mm × 5000 mm	60
LP1-60	(L series)	120

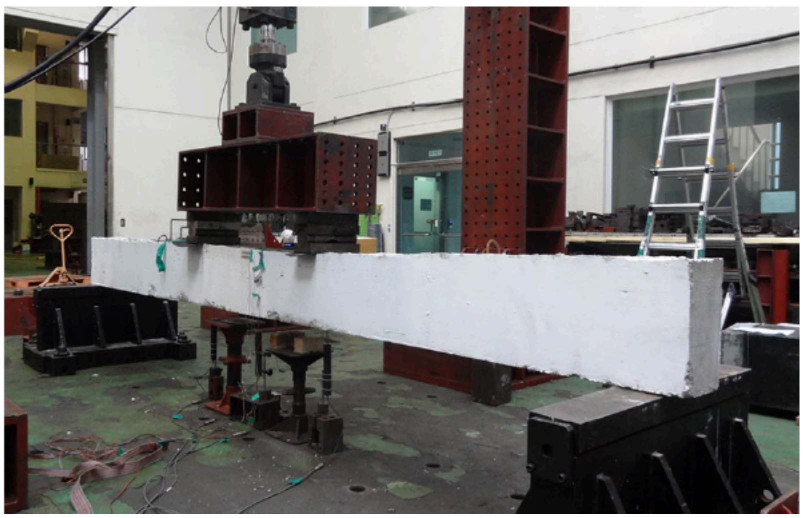


Figure 3-2. Residual Strength Test

The vertical displacement during the fire test and residual strength test is obtained with a linear variable differential transformer (LVDT) located at the center of the beam length, as illustrated in Fig. 3.2.

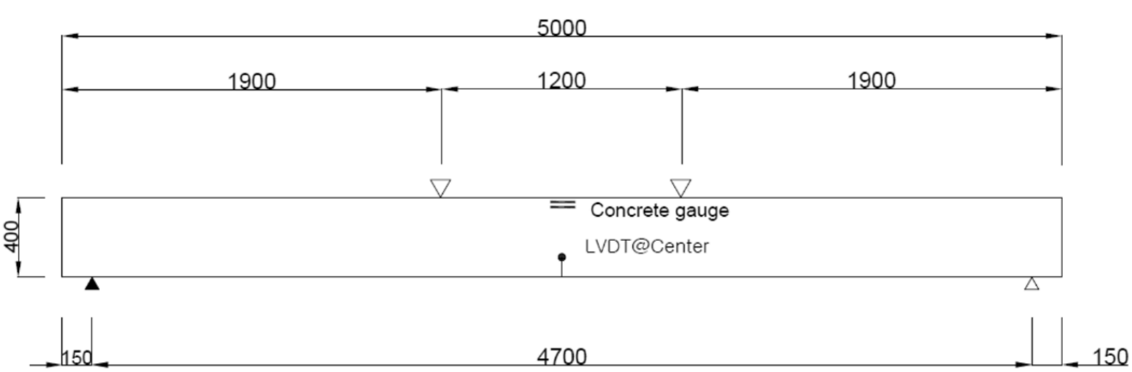


Figure 3-3. Set-up and detail of gauges and LVDT (unit: mm)

3.2.2. Experiment 2

This experiment has been performed by Moetaz M. El-Hawary, Ahmed M. RagabS, Ahmed Abd El-Aazim, and Shadia Elibiarif, 1996.

In this experiment, four RC beams were constructed with normal strength. The width, depth, and length of the RC beams are 120 mm × 200 mm × 1800 mm. The reinforcement arrangement for the rebars follow this order: two bars with a diameter of 10 mm grade 52 steel as the main reinforcement, two bars with 10 mm of diameter grade 37 steel as the secondary reinforcement, and stirrups with a diameter of 8 mm grade 37 at a spacing of 8 cm.

The curing time was the same for all of the beams and it was 28 days. The average of the compressive strength of the concrete after 28 days is 25 MPa.

The duration of fire exposure for beams was 30, 60, and 120 minutes. After fire exposure beams were sprayed with water immediately. Fire test and duration for each beam has been shown in Table 2. In order to measure residual capacity, all beams are subjected to the four-point bending test until the beam shows failure.

Table 3-2. Fire exposure duration

Beam number	Fire exposure duration (min)
B	0
B1	30
B2	60
B3	90

3.2.3. Experiment 3

This experiment has been performed by Yuye Xu, Bo Wu, Ming Jiang, and Xin Huang, 2012.

The width, depth, and length of the RC beams are 250 mm × 400 mm × 5000 mm.

The design of the beams follows the Code for Design of Concrete Structures (GB50010-2002). The average cubic compressive strength of the concrete after 28 days was 33.5 MPa. L1 specimen was the controlled sample. The fire scenario was following the ISO834 standard heating process 242 days after casting.

The overall view of the installation of the specimens in the furnace has been shown in Fig. 3.4.

The vertical displacement during the fire test and residual strength test is obtained with five Linear Voltage Displacement Transducers (LVDT) located at the center of the beam length, two of them under the loading points, and two of them at the supports.

Figure 3-4. overall view of the specimen in the furnace

3.2.4. Experiment 4

This experiment has been performed by Eun Gyu Choi, Yeongsoo Shin, and Heesun Kim, 2013.

In this experiment, twelve RC beams were constructed. The width, depth, and length of the RC beams are 250 mm × 400 mm × 4700 mm, as is shown in Figure 3.5. The reinforcement arrangement for the rebars are three bars with a diameter of 22 mm as main reinforcement and two bars with 22 mm of a diameter as secondary reinforcement. . In order to avoid shear failure stirrups with a diameter of 10 mm have been provided with a spacing of 15 cm, as illustrated in Figure 3.5.

Specimens includes normal and high strength concrete. In Table 3.3 list of specimens, fire exposure duration, concrete compressive strength, and concrete cover have been listed.

The heating of the furnace follows the ISO 834 standard time-temperature curve. In order to measure residual strength, a four-point loading test has been used.

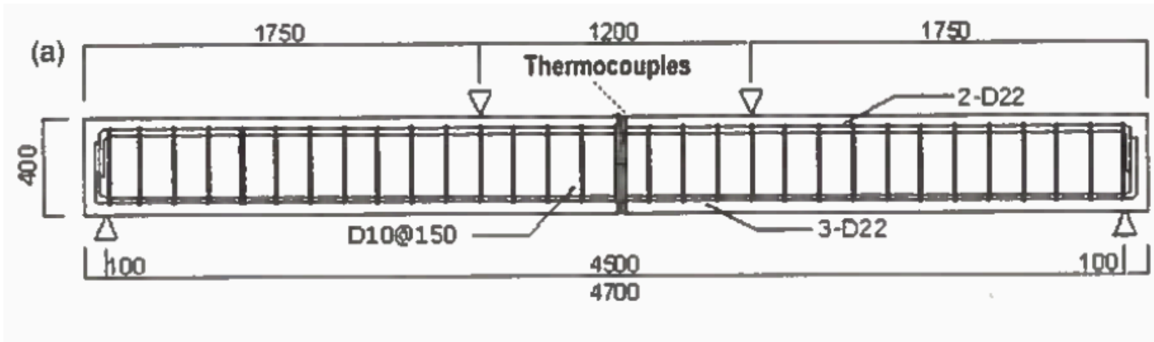


Figure 3-5. specimen dimensions

Table 3-3. Specimen List

Specimen	Fire Exposure Duration (min)	Concrete Compressive Strength (MPa)	Concrete Cover (mm)
N4-0	0	21	40
N4-1	60	21	40
N4-2	120	21	40
N5-0	0	21	50
N5-1	60	21	50
N5-2	120	21	50
H4-0	0	55	40
H4-1	60	55	40
H4-2	90	55	40
H5-0	0	55	50
H5-1	60	55	50
H5-2	90	55	50

3.3. The Output

Based on the Load-Deflection diagrams provided in the studies, the location of the gauges and the geometry of the beam moment capacity and applied moment were calculated.

In each series of beam, maximum applied momenta were compared together and the mean, standard variation, and coefficient of variation have been calculated for these maximum values.

All of the calculated values have been illustrated in tables in Appendix A.

4. Chapter 4

Reliability analysis

4.1. Introduction

Achieving the moment reduction factor for RC beams exposed to fire requires reliability analysis. To do so there are a couple of steps that have to be followed.

The first step is obtaining statistical parameters such as mean, COV, distribution from the experimental data. After modeling the load and resistance determining a limit state equation is the next step.

$$\varphi M_n \geq M_{tot} \qquad \text{(Eq. 4-1)}$$

Where

φ = Moment reduction factor

M_n = Moment capacity of the RC beam

M_{tot} = Applied moment on the RC beam

Geometry of the RC beam and loading condition as well as restraint are known factors in experiments. Therefore, the moment can be calculated. The highest moment capacity coming from the highest applied load on the control beam is the moment capacity of the RC beam, known as M_n . calculation of moment for M_{tot} have the same procedure. The difference is that M_n is only one value which is the highest value and also it is from the control beam. However, M_{tot} is all of the moments calculated from the loading that RC beam that has been exposed to fire experiences.

The procedure of the analysis have been shown in a flowchart.

In order to perform reliability analysis based on the Monte Carlo simulation, the variables should be defined in a distribution. Depending on each case it can be normal or lognormal distribution. In this study, lognormal distributions have been used. Based on the limit state equation, lognormal distribution has to be defined for M_n and M_{tot}.

To define distribution statistical parameters including mean and COV is needed. Since M_{tot} includes many numbers, these statistical parameters can be determined easily. But how a distribution can be defined for M_n? In the reliability analysis model, error need to be considered. This error should be 10 percent. The current study used an approach that considers this error as well as defining a distribution for M_n. In this approach, the constant M_n has been considered as the average of M_n with COV of 10 percent, which was the model error. Therefore, the variation of capacity which shows the error is covered.

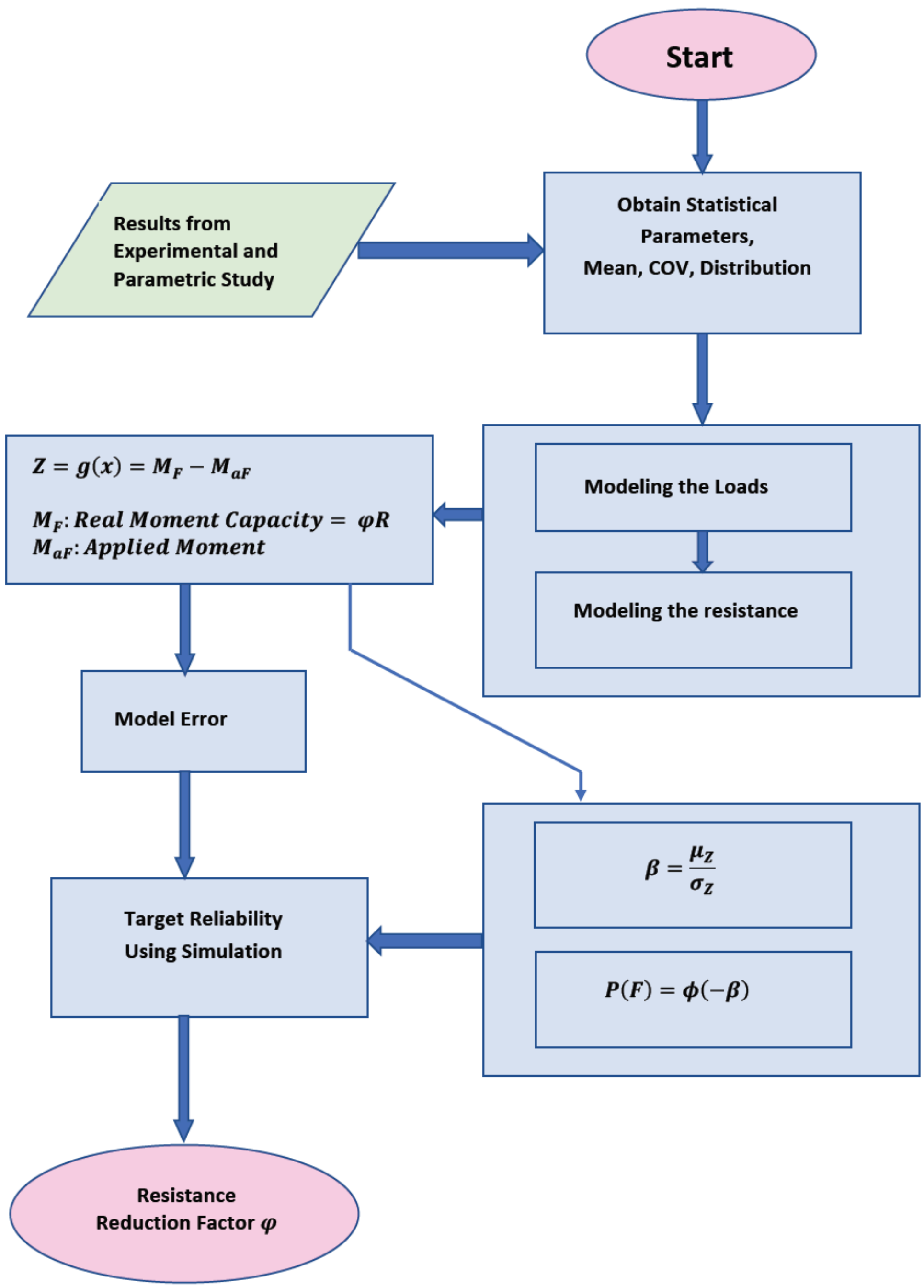


Figure 4-1. Reliability Analysis Flowchart

The coefficient of variation, COV is the ratio of the standard deviation divided by the mean. It is mostly expressed in percentage. The procedure of calculation of COV has been brought in equation 4-2.

$$COV = \frac{Standard\ Varioation}{Mean} = \frac{\sigma}{\mu} \quad \text{(Eq. 4-2)}$$

There are multiple samples therefore there are several M_{tot} and M_n distributions and each set of them gives a different phee factor. This study is based on the LRFD approach. Hence, the minimum amount of the phee should be selected between all.

In many design guidelines, it is suggested that value 1.0 is used in fire scenarios (Eurocode 3-2005). This suggestion has the root in the discussion that it is anticipated that live loads in elevated temperature situations are probable to be lesser than in the ambient temperature situation (Buchanan,2001). Anyhow, not much researches have been done to develop capacity reduction factors based on reliability analysis (Magnusson and Pettersson 1981).

All of the analysis have been written in a code in the Python language.

```
import matplotlib.pyplot as plt
import numpy as np
import scipy.stats
import statistics
from statistics import stdev

phee_list = []
phee_start = 0.01
phee_steps = 0.01
phee_end = 1
coef = int(phee_end/phee_steps)

def lower_bound_CI (data, confidence=0.95):
    a = 1.0 * np.array(data)
    n = len(a)
```

```
    m, se = np.mean(a), scipy.stats.sem(a)
    h = se * scipy.stats.t.ppf((1 + confidence) / 2., n-1)
    return m-h

def upper_bound_CI (data, confidence=0.95):
    a = 1.0 * np.array(data)
    n = len(a)
    m, se = np.mean(a), scipy.stats.sem(a)
    h = se * scipy.stats.t.ppf((1 + confidence) / 2., n-1)
    return m+h

#from scipy.stat import lognormal


Beams = input('Please enter number of beams:')
try:
    Beams = int(Beams)
except:
    print('Please enter an integer number')

for beam in range(Beams):
    print('Enter average for Mtot for beam #', (beam+1),':')
    mu = float(input())
    print('Enter StDev for Mtot for beam #', (beam+1),':')
    sigma = float(input())
    #mu, sigma = 260.9876, 0.2853
    Mtot = np.random.lognormal(mu,sigma,1000000)
    #Mtot = lognormal.cdf(1000000,mu,sigma)
    Mtot_list = Mtot.tolist()

    print('Please enter beam #', (beam+1), 'moment capacity average:')
    Ru = float(input())
```

```
    cov = 0.1
    StDev = cov * Ru



    check = False

    for i in range(int(phee_start*coef), int(phee_end*coef)+1):
        phee = i / coef
        Mn = np.random.lognormal((Ru*phee),(StDev*phee),1000000)
        #Mn = lognormal.cdf(1000000,(Ru*phee),(StDev*phee))
        Mn_list = Mn.tolist()

        if lower_bound_CI(Mn_list) < upper_bound_CI(Mtot_list):
            continue
        else:
            check = True
            print('For beam #',(beam+1), 'Mtot=', upper_bound_CI(Mtot_list), 'phee <=',
phee,'everything will be OK!\n\n')
            phee_list.append(phee)
            break



    if check == False:
        print("the Moment Capacity for beam #", (beam+1),"is too low to endure the load")

print('Minimun phee is', min(phee_list))
#for number in range(len(phee_list)):
        #    normal = (phee_list- statistics.mean(phee_list))/stdev(phee_list)
print("Target Reliability", 1-(len(phee_list)/1000000))

import numpy as np
```

```
from scipy.stats import norm
import matplotlib.pyplot as plt


# Generate some data for this demonstration.
data = norm.rvs(0.844, 0.414 , size=500)

# Fit a normal distribution to the data:
mu, std = norm.fit(data)

# Plot the histogram.
plt.hist(data, bins=25, density=True, alpha=0.6, color='g')

# Plot the PDF.
xmin, xmax = plt.xlim()
x = np.linspace(xmin, xmax, 100)
p = norm.pdf(x, mu, std)
plt.plot(x, p, 'k', linewidth=2)
title = "Fit results: mu = %.2f,  std = %.2f" % (mu, std)
plt.title(title)

plt.show()
```

4.2. Results and discussions:

The output result of the code has shown below:

results:

```
Please enter number of beams:12
Enter average for Mtot for beam # 1 :
```

```
300.81
Enter StDev for Mtot for beam # 1 :
3.51
Please enter beam # 1 moment capacity average:
302.47
For beam # 1 Mtot= 300.84531487357526 phee <= 1.0 everything will be O
K!


Enter average for Mtot for beam # 2 :
307.97
Enter StDev for Mtot for beam # 2 :
6.07
Please enter beam # 2 moment capacity average:
308.03
the Moment Capacity for beam # 2 is too low to endure the load
Enter average for Mtot for beam # 3 :
288.36
Enter StDev for Mtot for beam # 3 :
18.90
Please enter beam # 3 moment capacity average:
300.96
For beam # 3 Mtot= 288.4642470300231 phee <= 0.96 everything will be O
K!


Enter average for Mtot for beam # 4 :
401.24
Enter StDev for Mtot for beam # 4 :
195.27
Please enter beam # 4 moment capacity average:
326.16
the Moment Capacity for beam # 4 is too low to endure the load
Enter average for Mtot for beam # 5 :
803.11
Enter StDev for Mtot for beam # 5 :
```

```
384.42
Please enter beam # 5 moment capacity average:
1232.68
For beam # 5 Mtot= 805.8649295159945 phee <= 0.66 everything will be O
K!


Enter average for Mtot for beam # 6 :
239.76
Enter StDev for Mtot for beam # 6 :
44.41
Please enter beam # 6 moment capacity average:
308.76
For beam # 6 Mtot= 239.8094709247742 phee <= 0.78 everything will be O
K!


Enter average for Mtot for beam # 7 :
112.14
Enter StDev for Mtot for beam # 7 :
51.95
Please enter beam # 7 moment capacity average:
180.37
For beam # 7 Mtot= 112.52854876052196 phee <= 0.63 everything will be
OK!


Enter average for Mtot for beam # 8 :
138
Enter StDev for Mtot for beam # 8 :
69.20
Please enter beam # 8 moment capacity average:
180.37
For beam # 8 Mtot= 138.3626837467944 phee <= 0.77 everything will be O
K!
```

Enter average for Mtot for beam # 9 :

360.58

Enter StDev for Mtot for beam # 9 :

0.11

Please enter beam # 9 moment capacity average:

385.04

For beam # 9 Mtot= 360.58046862609837 phee <= 0.94 everything will be OK!

Enter average for Mtot for beam # 10 :

336.3

Enter StDev for Mtot for beam # 10 :

106.94

Please enter beam # 10 moment capacity average:

348.31

For beam # 10 Mtot= 337.2215095825051 phee <= 0.90 everything will be OK!

Enter average for Mtot for beam # 11 :

386.33

Enter StDev for Mtot for beam # 11 :

25.19

Please enter beam # 11 moment capacity average:

460.85

For beam # 11 Mtot= 386.5359718276704 phee <= 0.84 everything will be OK!

Enter average for Mtot for beam # 12 :

302.73

Enter StDev for Mtot for beam # 12 :

51.67

```
Please enter beam # 12 moment capacity average:
448.09
For beam # 12 Mtot= 303.0055162246844 phee <= 0.68 everything will be OK!


Minimun phee is 0.63
[1.0, 1.0, 1.0, 0.96, 1.0, 0.96, 1.0, 0.96, 0.66, 1.0, 0.96, 0.66, 0.78, 1.0, 0.96, 0.66, 0.78, 0.63, 1.0, 0.96, 0.66, 0.78, 0.63, 0.77, 1.0, 0.96, 0.66, 0.78, 0.63, 0.77, 0.94, 1.0, 0.96, 0.66, 0.78, 0.63, 0.77, 0.94, 0.97, 1.0, 0.96, 0.66, 0.78, 0.63, 0.77, 0.94, 0.97, 0.84, 1.0, 0.96, 0.66, 0.78, 0.63, 0.77, 0.94, 0.97, 0.84, 0.68]
```

Figure 4-2 shows the distribution of the phee factors. The code was run by experiment result and the output was numbers of phee factors depicted in figure 4-2.

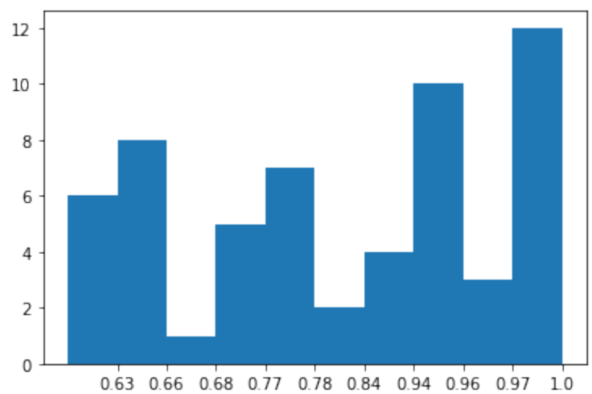


Figure 4-2. Phee factor distribution

It can be observed from the figure and other results that most of the output numbers are mostly ranged between 0.63 to 1.

Considering the building type in order to use the φ factor is recommended. For the buildings with a high level of importance such as hospitals lesser value for φ factor is recommended, also for less important buildings such as warehouses higher value of φ can be suggested.

The normal distribution for the factor has been shown in figure 4-3.

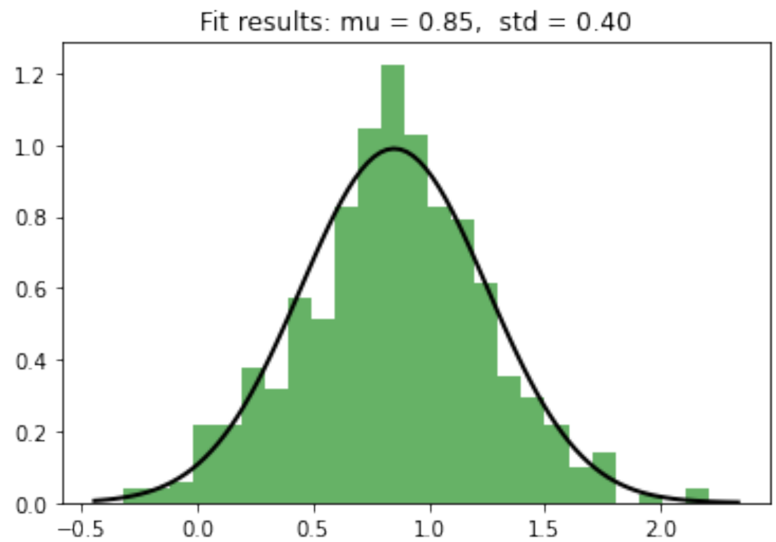


Figure 4-3. Normal distribution of φ factor

By considering experiment conditions and phee factor results, it can be seen by increasing the size of the section the phee factor decreases. Also by an increment in compressive strength of the concrete and change from NSC to HSC, the phee factor decreases significantly. Furthermore, change in the concrete cover can cause a decrement in the phee factor.

Table 4-1. change in parameters and φ value

Experiment Series Number	Accepted (A) Rejected (R)	φ value	Change of Parameter	
1	A	1	Increase In Loading	Increase In Loading And Dimension
2	R	-		
3	A	0.96		
4	R	-	Increase In Section Size	
5	A	0.66		
6	A	0.78		
7	A	0.63	Increase In Cross-Section Area	
8	A	0.77		

9	A	0.94	Increase	Increase In
10	A	0.90	In Cover	Concrete
11	A	0.84	Increase	Compressive
12	A	0.68	In Cover	Strength

5. Chapter 5

Conclusion

In the design of structures, the fire hasn't been comprehensively include in new design methods such as LRFD. The current study was conducted with the goal to fill this gap, it contained two parts. The first part comprised a numerical study based on previously conducted experiments from other studies. In the second part, a reliability analysis was conducted, this analysis was done by using a code that has been written in the Python language. The summary of the findings has been described in the following sections.

5.1. Summary of conclusions

By considering experiment conditions and phee factor results, it can result that by increasing the size of the section the phee factor decreases. Also by an increment in compressive strength of the concrete and change from NSC to HSC, the phee factor decreases significantly. Furthermore, increase in the concrete cover can cause a decrement in the phee factor.

It can be observed that most of the output numbers for the phee factor are mostly ranged between 0.63 to 1.

5.2. Future studies

The following includes recommendations for future studies:

- The beams that have been used for numerical study only included RC beams. It is recommended that the effect of FRP (Fiber Reinforced Polymer) strengthened concrete beams be considered in future researches.
- The studied beams were RC beams, including composite beams in future researches can be helpful.
- The numerical study was conducted on beams. Considering other parts of structures and developing phee factors for them are recommended.

Appendix A

Moment Capacity and Applied Moments

Experiment 1

P1 Series

Overall calculation

	Loading (kN)			Mtot (kN.m)			Control Beam
Deflection (mm)	60 min	90 min	120 min	60 min	90 min	120 min	Loading (kN)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	4.95	4.95	3.96	8.66	8.66	6.93	2.96
0.01	8.91	9.40	6.93	15.59	16.45	12.12	6.42
0.46	10.39	14.35	11.88	18.19	25.12	20.79	9.38
0.47	16.33	17.82	16.33	28.58	31.18	28.58	12.35
1.37	20.29	20.79	20.29	35.51	36.37	35.51	14.81
1.37	24.25	24.74	26.23	42.44	43.30	45.90	18.27
1.82	29.20	27.71	31.18	51.10	48.50	54.56	21.23
2.28	32.67	32.66	37.61	57.17	57.16	65.82	25.19
3.17	40.09	37.12	44.05	70.16	64.96	77.08	29.14
3.62	44.54	42.07	47.51	77.95	73.62	83.15	32.59

4.52	50.48	47.02	50.48	88.35	82.28	88.34	36.54
5.42	53.95	51.97	55.43	94.41	90.94	97.00	40.00
5.87	57.41	56.42	60.38	100.47	98.74	105.66	42.47
6.32	59.89	60.88	64.34	104.80	106.53	112.59	44.94
7.66	63.85	64.34	68.30	111.73	112.60	119.52	47.90
9.00	69.79	68.30	73.74	122.13	119.52	129.05	52.84
9.46	73.75	72.26	78.20	129.05	126.45	136.85	58.77
10.80	76.72	76.22	82.16	134.25	133.38	143.77	63.21
11.69	83.64	80.18	86.12	146.38	140.31	150.70	66.67
11.70	86.61	84.14	91.56	151.58	147.24	160.23	70.12
13.05	92.06	87.60	97.01	161.10	153.31	169.76	76.05
13.95	95.52	91.56	102.45	167.17	160.23	179.29	80.99
14.85	99.48	94.53	105.91	174.10	165.43	185.35	86.42
15.75	103.44	98.49	109.87	181.02	172.36	192.28	94.32
17.99	109.38	101.96	113.34	191.42	178.42	198.34	102.22
18.89	116.31	104.43	118.29	203.54	182.75	207.00	108.15
20.69	119.78	108.39	121.26	209.61	189.68	212.20	117.04
22.03	122.75	110.87	126.21	214.80	194.01	220.86	123.46
23.38	124.73	115.32	129.67	218.27	201.81	226.92	129.88
24.06	127.20	118.29	133.63	222.60	207.01	233.86	136.30

26.07	129.68	121.75	137.59	226.93	213.07	240.78	143.70
26.98	133.63	125.22	142.54	233.86	219.13	249.45	151.60
28.33	140.07	128.19	147.49	245.12	224.33	258.11	158.02
30.11	143.53	132.15	151.45	251.18	231.26	265.04	162.47
31.01	147.00	136.11	157.39	257.25	238.19	275.43	165.93
31.90	150.96	140.07	160.85	264.18	245.12	281.49	168.89
33.24	153.43	143.04	163.82	268.51	250.31	286.69	170.37
34.57	156.40	147.49	164.31	273.70	258.11	287.55	169.88
36.35	159.37	149.97	166.79	278.90	262.44	291.88	170.86
37.68	162.34	153.43	167.78	284.09	268.50	293.61	170.86
38.57	165.31	157.89	168.76	289.29	276.30	295.34	171.85
39.90	169.76	160.36	167.77	297.09	280.63	293.60	172.35
41.24	171.74	163.82	168.27	300.55	286.69	294.47	172.84
43.01	172.73	166.30	154.42	302.27	291.02	270.23	171.85
44.78	172.73	168.77	123.73	302.27	295.35	216.53	169.88
49.22	167.78	169.76	167.77	293.62	297.07	293.60	168.89
50.99	173.71	169.75	169.75	304.00	297.07	297.06	167.41
52.77	174.21	170.25	170.74	304.86	297.93	298.79	166.91
54.98	174.20	170.24	169.25	304.86	297.93	296.19	164.44
57.65	170.24	170.74	167.27	297.92	298.79	292.72	164.44

60.31	169.25	168.26	168.25	296.18	294.45	294.45	164.94
63.42	167.26	162.81	167.76	292.70	284.92	293.57	164.94
67.86	164.29	161.82	165.77	287.50	283.18	290.10	164.94
74.52	161.81	159.83	164.78	283.17	279.70	288.36	164.44
77.62	160.32	158.34	165.27	280.56	277.09	289.22	161.48
81.17	159.33	155.86	164.76	278.82	272.76	288.34	160.99
83.39	156.85	153.38	166.25	274.48	268.42	290.93	160.99
86.50	157.34	150.41	167.24	275.35	263.22	292.66	161.48
90.06	157.34	147.44	166.74	275.34	258.01	291.79	161.98
93.17	156.84	146.94	166.74	274.47	257.14	291.79	162.47
96.72	156.83	146.94	164.75	274.46	257.14	288.32	162.47
101.60	156.83	146.44	164.75	274.46	256.26	288.31	162.47
104.71	156.83	140.99	165.24	274.45	246.73	289.16	162.96
107.82	156.82	142.96	165.72	274.44	250.18	290.01	162.96
110.04	156.82	144.93	163.74	274.44	253.63	286.54	163.95
114.93	153.85	144.92	157.79	269.23	253.62	276.14	163.95
119.81	152.36	141.94	124.13	266.63	248.40	217.23	162.96
123.36	149.88	133.03	106.31	262.29	232.81	186.04	162.96
126.47	148.89	118.67	63.24	260.56	207.68	110.67	163.46
131.36	150.37	110.26		263.15	192.95		163.46

134.46	149.88	102.83		262.28	179.96		162.47
137.57	149.87	94.91		262.28	166.10		160.00
140.23	149.87	81.05		262.27	141.84		161.48
142.45	149.87			262.26			160.49
145.12	149.37			261.39			161.48
147.78	148.37			259.65			161.98
150.89	147.87			258.78			161.98
154.00	142.42			249.24			161.98
155.33	137.47			240.57			161.98
157.55	133.01			232.77			159.51
158.87	128.56			224.98			156.54
161.10	122.62			214.58			158.02
165.54	115.19			201.58			159.01
168.20	109.25			191.19			159.01
170.87	101.33			177.32			160.00
173.98	90.43			158.26			159.51
176.64	79.05			138.33			160.00
179.75							160.00
183.30							160.00
186.41							160.00

190.85							160.00
194.85							159.01
198.84							158.02
202.84							157.53
206.39							156.05
209.94							155.06
213.48							153.58
216.14							151.11
217.03							149.14

	Deflection (mm)	Loading (kN) 60 min	90 min	120 min	Mtot (kN.m) 60 min	90 min	120 min	Control Beam Loading (kN)
Mean	80.26	120.02	110.61	117.73	210.03	193.56	206.03	129.39
STD	69.61	49.68	50.20	54.49	86.95	87.85	95.35	54.11
COV	0.87	0.41	0.45	0.46	0.41	0.45	0.46	0.42
Max	217.03	174.21	170.74	170.74	304.86	298.79	298.79	172.84

Inputs for the code:

Mn (kN.m)	Mtot (kN.m) Mean	STD	COV
302.47	300.81	3.51	0.01

P2 Series

Overall calculation

	Loading (kN)		Mtot (kN.m)		Control Beam
Deflection (mm)	60 min	120 min	60 min	120 min	Loading (kN)
0.00	0.00	0.00	0.00	0.00	0.00
0.44	5.88	5.39	10.29	9.44	10.73
1.76	11.76	11.76	20.59	20.59	20.00
3.53	18.14	21.57	31.74	37.75	29.27
5.29	24.51	27.94	42.89	48.90	38.05
7.50	29.90	34.80	52.33	60.91	47.32
9.70	36.76	52.94	64.34	92.65	57.07
11.90	40.69	60.29	71.20	105.51	66.34
13.23	47.06	70.10	82.35	122.67	74.63
14.99	52.94	78.43	92.65	137.25	83.90
16.31	58.82	85.29	102.94	149.26	93.66
18.08	62.75	94.61	109.80	165.56	101.46
19.40	66.67	100.49	116.67	175.86	112.20

21.60	71.08	106.86	124.39	187.01	122.44
23.37	80.39	114.71	140.69	200.74	131.71
24.69	91.67	122.55	160.42	214.46	140.49
26.90	99.51	129.41	174.14	226.47	149.76
29.54	111.27	137.25	194.73	240.20	160.98
31.31	119.12	144.61	208.46	253.06	166.83
33.51	127.94	150.00	223.90	262.50	169.76
36.16	135.78	157.35	237.62	275.37	169.76
38.36	145.10	161.27	253.92	282.23	171.71
40.56	153.43	164.71	268.50	288.24	173.17
42.33	160.78	168.63	281.37	295.10	176.02
44.53	167.16	172.06	292.52	301.10	170.73
48.06	172.55	173.53	301.96	303.68	169.76
49.38	175.98	171.08	307.97	299.39	167.80
52.91	178.43	171.57	312.25	300.25	167.80
54.23	177.94	170.10	311.40	297.67	165.37
57.32	174.02	168.63	304.53	295.10	164.88
60.85	173.53	168.14	303.68	294.24	164.88
63.93	170.10	166.67	297.67	291.67	165.37
68.78	165.69	165.20	289.95	289.09	164.88

70.99	163.73	165.20	286.52	289.09	163.90
74.51	163.24	163.24	285.66	285.66	163.90
77.60	161.27	161.76	282.23	283.09	161.46
81.57	160.29	161.27	280.51	282.23	160.49
86.42	160.78	161.27	281.37	282.23	161.46
91.27	161.27	158.33	282.23	277.08	161.95
97.00	161.27	157.84	282.23	276.23	161.95
100.97	160.78	157.84	281.37	276.23	161.95
104.06	160.78	154.90	281.37	271.08	162.93
108.02	158.82	148.53	277.94	259.93	163.41
111.55	157.84	139.22	276.23	243.63	163.90
116.84	157.35	126.47	275.37	221.32	162.93
121.69	152.45	105.88	266.79	185.29	162.44
126.10	144.12	80.88	252.21	141.54	163.41
130.07	129.90		227.33		163.41
133.16	98.53		172.43		162.93
135.80	72.55		126.96		161.95
137.13					160.00
139.77					161.46
143.30					161.46

147.71					161.95
151.23					161.46
156.08					161.46
158.73					156.10
160.93					158.54
164.02					159.02
171.08					159.02
175.49					159.51
180.34					160.49
183.86					160.00
189.15					160.00
194.00					159.51
199.29					158.54
203.70					157.56
207.67					156.10
210.76					155.12
213.84					153.17
216.49					150.24
217.37					145.37
216.93					141.46

		Loading (kN)		Mtot (kN.m)		Control Beam
	Deflection (mm)	60 min	120 min	60 min	120 min	Loading (kN)
Mean	95.86	116.65	122.78	204.13	214.86	141.71
STD	70.32	56.72	52.79	99.26	92.39	43.07
COV	0.73	0.49	0.43	0.49	0.43	0.30
Max	217.37	178.43	173.53	312.25	303.68	176.02

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
308.03	307.97	6.07	0.02

P3 Series

Overall calculation

	Loading (kN)		Mtot (kN.m)		Control Beam
Deflection (mm)	60 min	120 min	60 min	120 min	Loading (kN)
0.00	0.00	0.00	0.00	0.00	0.00
0.88	4.43	3.94	7.76	6.90	9.31
2.65	12.81	9.36	22.41	16.38	21.07
3.53	17.24	14.78	30.17	25.86	30.39
5.74	26.60	22.66	46.55	39.66	40.18
7.95	31.53	29.56	55.17	51.72	49.49
10.60	41.38	38.92	72.41	68.10	59.29
11.93	45.32	46.31	79.31	81.03	68.60
13.25	52.71	54.68	92.24	95.69	79.39
15.46	57.14	62.07	100.00	108.62	87.71
16.78	70.44	70.94	123.28	124.14	98.01
19.43	78.33	81.77	137.07	143.10	108.30
20.76	82.27	90.15	143.97	157.76	119.08

22.97	89.16	98.03	156.03	171.55	129.37
24.29	97.54	103.94	170.69	181.90	138.68
26.06	102.46	108.87	179.31	190.52	147.01
28.27	109.36	115.76	191.38	202.59	156.32
31.36	113.79	126.60	199.14	221.55	166.11
34.89	122.66	137.93	214.66	241.38	169.54
38.43	126.11	145.81	220.69	255.17	170.51
41.52	138.92	153.20	243.10	268.10	171.98
43.73	148.28	157.14	259.48	275.00	170.01
46.82	157.64	160.10	275.86		169.52
49.03	167.49	161.58	293.10		167.55
51.68	171.92	161.58	300.86		167.06
54.33	172.41	160.10	301.72		165.09
58.30	170.44	158.13	298.28		164.59
60.95	170.94	158.62	299.14		165.08
63.60	171.43	159.11	300.00		165.07
68.02	167.00	159.61	292.24		164.57
70.23	165.02	161.08	288.79		163.59
74.20	162.07	162.07	283.62		163.09
78.18	162.56	161.58	284.48		160.63

81.71	163.05	168.47	285.34		160.62
84.81	163.05	172.91	285.34		160.62
88.78	163.05	175.86	285.34		161.10
92.31	163.05	171.43	285.34		161.58
94.96	163.05	169.95	285.34		161.58
99.38	162.56	168.47	284.48		161.57
102.92	162.07	159.61	283.62		161.56
107.33	161.08	147.78	281.90		162.53
110.87	157.64	138.92	275.86		163.02
116.17	156.65	123.65	274.14		163.01
120.58	148.77	110.84	260.34		162.02
125.88	135.47	91.63	237.07		162.50
129.86	122.17	69.95	213.79		162.98
133.39	107.39		187.93		161.99
137.37	91.13		159.48		159.53
141.34	78.82		137.93		160.51
147.08					161.48
151.94					160.98
155.48					160.97
158.13					155.57

160.78					158.02
164.31					158.50
168.29					158.98
173.14					158.97
177.56					159.46
179.77					157.98
183.30					158.95
187.28					159.44
191.70					159.43
196.11					157.95
200.97					156.96
205.39					155.97
209.36					154.98
212.46					153.50
214.66					150.56
216.87					147.61
217.31					143.20
217.31					139.28
216.87					135.36

		Loading (kN)		Mtot (kN.m)		Control Beam
	Deflection (mm)	60 min	120 min	60 min	120 min	Loading (kN)
Mean	99.58	116.46	115.34	203.80	133.03	141.07
STD	71.23	54.10	55.05	94.67	89.61	42.42
COV	0.72	0.46	0.48	0.46	0.67	0.30
Max	217.31	172.41	175.86	301.72	275.00	171.98

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
300.96	288.36	18.90	0.07

MP1 Series

Overall calculation

	Loading (kN)	Mtot (kN.m)	Control Beam
Deflection (mm)	60 min	60 min	Loading (kN)
0.00	0.00	0.00	1.46
0.44	11.74	20.54	8.27
1.32	19.56	34.23	18.00
2.20	28.36	49.63	27.25
3.95	35.21	61.61	37.47
5.71	46.94	82.15	48.18
7.47	58.68	102.69	58.88
8.79	67.48	118.09	65.69
10.11	78.24	136.92	74.94
11.42	89.98	157.46	80.78
12.30	100.73	176.28	91.48
14.94	112.47	196.82	104.14
16.26	125.18	219.07	115.82

18.45	139.85	244.74	128.95
20.65	154.52	270.42	143.55
22.85	164.30	287.53	155.23
25.92	178.97	313.20	167.88
28.12	190.71	333.74	176.64
31.20	201.47	352.57	182.00
34.27	208.31	364.55	182.48
33.83	215.16	376.53	180.05
32.51	223.96	391.93	182.00
35.59	238.63	417.60	183.45
36.47	248.41	434.72	181.51
36.91	258.19	451.83	184.43
38.22	266.99	467.24	183.45
39.10	276.77	484.35	185.40
39.54	284.60	498.04	183.94
39.98	297.31	520.29	181.51
39.98	310.02	542.54	179.56
41.74	321.76	563.08	183.45
41.74	335.45	587.04	185.89
43.06	346.21	605.87	186.37

45.25	352.08	616.14	186.37
49.21	357.95	626.41	184.91
50.09	360.88	631.54	182.00
50.97	361.86	633.25	179.08
53.16	362.84	634.96	175.18
56.24	364.79	638.39	174.21
59.31	359.90	629.83	172.75
62.39	354.03	619.56	171.78
64.15	346.21	605.87	169.34
66.78	342.30	599.02	166.42
68.98	338.39	592.18	167.88
73.37	333.50	583.62	168.37
75.13	332.52	581.91	169.34
78.65	323.72	566.50	169.34
82.60	316.87	554.52	169.83
86.12	306.11	535.70	168.86
89.63	291.44	510.02	168.86
93.15	275.79	482.64	169.34
96.22	262.10	458.68	169.34
99.74	246.45	431.30	168.86

104.57	230.81	403.91	168.37
108.96	221.03	386.80	165.94
114.24	204.40	357.70	164.96
117.75	186.80	326.89	165.94
119.51			161.56
122.58			156.69
124.34			146.96
126.54			141.61
127.86			136.25
129.17			132.36
130.49			128.95
132.69			125.55
136.20			123.11
139.72			119.71
143.23			116.79
147.19			114.84
152.02			111.92
157.29			108.03
162.13			103.65
167.40			96.35

	Deflection (mm)	Loading (kN) 60 min	Mtot (kN.m) 60 min	Control Beam Loading (kN)
Mean	67.08	229.28	401.24	142.49
STD	48.52	111.58	195.27	48.25
COV	0.72	0.49	0.49	0.34
Max	167.40	364.79	638.39	186.37

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
326.16	401.24	195.27	0.49

LP1 Series

Overall calculation

Deflection	Loading (kN) 60 min	Mtot (kN.m) 60 min	Control Beam Loading (kN)
0.00	0.00	0.00	0.00
0.43	21.11	36.94	24.94
0.86	38.38	67.16	53.72
1.29	53.74	94.04	80.59
1.29	76.76	134.33	101.69
1.72	101.71	177.99	128.55
2.59	120.90	211.57	145.82
3.45	145.85	255.24	168.85
4.31	161.20	282.11	186.12
5.17	178.47	312.33	212.99
6.03	195.75	342.56	236.02
7.76	216.85	379.49	262.89
8.19	243.72	426.51	285.91
9.05	260.99	456.73	305.11

9.05	282.10	493.67	322.37
11.21	308.96	540.68	351.17
11.64	333.91	584.35	378.03
12.07	358.86	628.00	402.97
13.36	379.97	664.95	424.08
14.22	401.07	701.88	449.03
15.95	422.18	738.82	475.90
15.95	445.21	779.12	477.82
16.38	470.16	822.77	500.85
17.24	489.35	856.36	531.55
18.53	508.55	889.96	564.17
19.40	529.66	926.90	589.12
21.12	545.01	953.77	621.74
22.41	562.28	983.99	650.53
23.71	585.31	1024.29	669.73
26.72	608.34	1064.59	690.85
27.16	629.45	1101.53	669.75
28.88	646.72	1131.76	687.03
31.90	662.08	1158.63	677.46
33.19	677.45	1185.53	700.49

36.21	683.22	1195.64	683.25
37.50	683.26	1195.71	702.45
40.52	683.29	1195.76	704.39
40.95	690.99	1209.24	681.37
43.97	691.01	1209.27	677.56
44.40	679.49	1189.11	662.21
46.98	685.25	1199.19	679.50
47.41	679.50	1189.13	654.56
50.00	671.83	1175.70	679.52
50.86	675.68	1182.44	656.51
52.59	668.01	1169.02	669.95
53.45	664.20	1162.34	654.61
56.47	658.47	1152.32	673.81
57.76	648.89	1135.57	654.64
60.34	641.24	1122.17	664.25
61.64	629.76	1102.07	648.91
63.79	608.67	1065.17	662.36
64.66	587.59	1028.28	648.94
66.81	566.50	991.37	658.55
68.53	535.82	937.69	637.46

71.98	510.90	894.07	648.99
74.14	484.06	847.11	633.66
77.59	468.72	820.27	650.96
78.88	436.13	763.22	637.54
82.33	411.21	719.62	647.15
83.62	399.72	699.51	624.14
88.79	380.56	665.98	641.45
89.22	340.28	595.49	622.27
93.53	298.08	521.64	635.73
96.98	263.57	461.24	630.00
97.41	232.89	407.55	612.74
101.29	206.02	360.54	618.52
101.72			599.34
106.47			603.22
107.76			587.88
112.07			584.07
115.52			570.67
118.53			561.10
123.71			540.04
128.88			518.97

133.19			494.07
137.50			469.16
141.38			436.58
145.69			407.83
149.14			375.25
153.88			348.42
160.78			317.78
161.64			287.09
159.91			252.55
158.19			225.67
156.90			202.64

		Loading	Mtot (kN.m)	Control Beam
	Deflection (mm)	60 min	60 min	Loading (kN)
Mean	68.49	441.32	891.96	554.44
STD	47.50	155.18	271.56	140.71
COV	0.69	0.35	0.30	0.25
Max	161.64	691.01	1209.27	704.39

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
1232.68	803.11	384.42	0.48

Experiment 2

Overall calculation

	Loading (Ton)			moment (kN.m)			control beam	
deflection (mm)	30 min	60 min	120 min	30 min	60 min	120 min	loading (Ton)	moment (kN.m)
1.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.55	124.37	108.56	108.27	6.95	6.07	6.05	187.36	10.48
12.94	202.02	217.55	170.09	11.30	12.16	9.51	327.79	18.33
20.34	310.91	279.66	232.02	17.39	15.64	12.97	468.22	26.18
27.73	419.80	357.35	278.36	23.47	19.98	15.57	593.03	33.16
40.68	544.08	403.89	340.28	30.42	22.58	19.03	764.57	42.75
48.07	621.53	465.86	402.35	34.75	26.05	22.50	873.75	48.86
62.87	745.91	543.46	433.12	41.71	30.39	24.22	1045.24	58.45
73.96	792.45	605.67	463.74	44.31	33.87	25.93	1138.70	63.67
85.05	870.09	683.50	525.66	48.65	38.22	29.39	1232.16	68.90
94.30	978.79	776.63	587.59	54.73	43.43	32.86	1325.67	74.13
107.24	1119.08	885.33	649.46	62.58	49.50	36.32	1434.71	80.22
118.34	1274.56	994.08	711.09	71.27	55.59	39.76	1528.17	85.45
134.98	1383.59	1087.44	788.50	77.37	60.81	44.09	1683.98	94.16
149.77	1508.11	1133.93	834.55	84.33	63.41	46.67	1792.97	100.26

162.71	1601.53	1211.72	912.05	89.55	67.76	51.00	1886.39	105.48
181.20	1725.85	1289.36	973.83	96.50	72.10	54.45	2026.53	113.32
194.14	1881.57	1367.01	1035.56	105.21	76.44	57.91	2198.07	122.91
205.24	2006.04	1475.85	1081.81	112.17	82.53	60.49	2275.91	127.26
216.33	2114.89	1584.51	1128.20	118.26	88.60	63.09	2369.37	132.49
225.58	2208.20	1708.78	1158.78	123.48	95.55	64.80	2447.25	136.84
236.67	2317.00	1801.95	1236.18	129.56	100.76	69.12	2540.71	142.07
251.46	2472.77	1926.43	1329.02	138.27	107.72	74.31	2665.33	149.04
262.56	2550.41	2066.42	1359.59	142.61	115.55	76.02	2790.04	156.01
277.35	2659.21	2190.94	1406.03	148.70	122.51	78.62	2883.40	161.23
292.14	2721.37	2346.52	1468.10	152.17	131.21	82.09	2992.39	167.33
306.93	2799.02	2533.10	1529.88	156.51	141.64	85.55	3117.01	174.29
318.03	2861.28	2657.53	1591.75	159.99	148.60	89.01	3210.47	179.52
332.82	2970.07	2735.27	1638.00	166.08	152.95	91.59	3335.08	186.49
349.46	3063.29	2844.01	1699.83	171.29	159.03	95.05	3428.40	191.71
364.25	3172.19	2984.11	1777.28	177.38	166.86	99.38	3553.01	198.67
377.20	3265.36	3077.23	1854.73	182.59	172.07	103.71	3646.43	203.90
390.14	3374.21	3154.93	1924.70	188.68	176.41	107.62	3739.84	209.12
406.78	3498.58	3263.82	1994.25	195.63	182.50	111.51	3880.03	216.96
425.27	3607.47	3356.94	2087.27	201.72	187.71	116.71	4004.55	223.92

441.91	3731.85	3450.16	2164.82	208.67	192.92	121.05	4129.12	230.89
456.70	3902.81	3527.76	2226.84	218.23	197.26	124.52	4253.73	237.86
475.19	3964.78	3605.31	2304.43	221.70	201.60	128.86	4393.88	245.69
493.68	4058.14	3729.54	2382.03	226.92	208.54	133.20	4487.14	250.91
512.17	4135.93	3822.66	2428.47	231.27	213.75	135.79	4658.54	260.49
528.81	4198.09	3915.74	2521.69	234.74	218.96	141.01	4767.48	266.58
543.61	4260.30	3993.28	2599.24	238.22	223.29	145.34	4860.84	271.80
556.55	4322.47	4055.11	2692.41	241.70	226.75	150.55	4954.26	277.03
573.19	4477.85	4179.29	2754.62	250.39	233.69	154.03	5031.95	281.37
586.13	4555.54	4241.26	2816.64	254.73	237.16	157.50	5109.74	285.72
604.62	4633.19	4318.62	2941.06	259.07	241.48	164.46	5203.00	290.94
621.26	4726.55	4403.93	3049.72	264.29	246.25	170.53	5311.95	297.03
636.06	4804.19	4489.24	3127.31	268.64	251.02	174.87	5374.06	300.50
649.00	4866.31	4535.63	3220.44	272.11	253.62	180.08	5436.22	303.98
667.49	4928.38		3399.26	275.58		190.08	5521.68	308.76

		Loading(Ton)			Moment (kN.m)			Control Beam	
	Deflection (mm	30 min	60 min	120 min	30 min	60 min	120 min	Loading (Ton)	Moment (kN.m)
Mean	302.13	2586.64	2252.79	1526.82	144.64	125.97	85.38	2937.60	164.26
STD	203.92	1508.65	1437.58	950.06	84.36	80.38	53.12	1637.02	91.54
COV	0.67	0.58	0.64	0.62	0.58	0.64	0.62	0.56	0.56
Max	667.49	4928.38	4535.63	3399.26	275.58	253.62	190.08	5521.68	308.76

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
308.76	239.76	44.41	0.19

Experiment 3

L2 Series

Overall calculation

	L2	Control Beam
Deflection (mm)	Moment (KN.m)	Moment (KN.m)
0.00	0.00	0.00
2.10	12.82	11.20
3.49	20.82	18.41
4.89	32.84	24.81
5.94	44.05	32.01
7.51	56.87	39.22
8.91	69.68	48.82
10.31	81.69	57.62
11.71	94.51	65.62
12.93	104.12	75.22
14.50	112.94	84.02
16.25	116.94	95.22

18.17	121.75	105.62
19.40	127.36	113.62
20.97	134.57	121.63
22.54	139.37	130.43
24.11	143.39	137.63
25.51	146.61	144.04
27.43	149.82	148.06
29.88	152.23	154.47
31.98	153.05	161.69
34.42	155.45	168.10
37.22	157.87	168.94
39.84	158.67	170.57
42.98	158.68	171.40
45.95	162.70	173.83
49.62	164.31	176.27
53.12	166.73	177.91
58.19		180.37

		L2	Control Beam
	Deflection (mm)	Moment (KN.m)	Moment (KN.m)
Mean	23.44	112.14	108.85
STDEV	16.36	51.95	59.78
COV	0.70	0.46	0.55
Max	58.19	166.73	180.37

Inputs for the code:

	Mtot (KN.m)		
Mn (KN.m)	Mean	STD	COV
180.37	112.14	51.95	0.46

L3 Series

Overall calculation

	L2	Control Beam
Deflection (mm)	Moment (KN.m)	Moment (KN.m)
0.00	0.00	0.00
2.10	15.19	11.20
3.49	29.58	18.41
4.89	39.18	24.81
5.94	56.76	32.01
7.51	66.36	39.22
8.91	77.56	48.82
10.31	92.75	57.62
11.71	105.54	65.62
12.93	119.14	75.22
14.50	134.33	84.02
16.25	147.93	95.22
18.17	158.32	105.62

19.40	167.92	113.62
20.97	181.52	121.63
22.54	191.14	130.43
24.11	196.75	137.63
25.51	198.36	144.04
27.43	198.37	148.06
29.88	199.18	154.47
31.98	199.99	161.69
34.42	200.79	168.10
37.22	201.60	168.94
39.84	202.42	170.57
42.98	203.22	171.40
45.95	204.03	173.83
49.62		176.27
53.12		177.91
58.19		180.37

	Deflection (mm)	L2 Moment (KN.m)	Control Beam Moment (KN.m)
Mean	23.44	138.00	108.85
STDEV	16.36	69.20	59.78
COV	0.70	0.50	0.55
Max	58.19	204.03	180.37

Inputs for the code:

	Mtot (KN.m)		
Mn (KN.m)	Mean	STD	COV
180.37	138.00	69.20	0.50

Experiment 4

N4 Series

Overall calculation

	Loading (kN)		Moment (kN.m)		Control Beam	
Deflection (mm)	N4-1	N4-2	N4-1	N4-2	Load (kN)	Moment (kN.m)
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.58	9.34	11.49	16.34	20.10	15.81	27.67
2.26	18.66	25.84	32.66	45.22	27.28	47.75
3.57	27.99	38.75	48.98	67.81	40.20	70.35
5.06	35.88	51.65	62.78	90.38	54.55	95.47
5.63	45.91	65.27	80.35	114.22	63.89	111.81
6.57	55.23	78.18	96.66	136.82	73.22	128.14
8.24	64.55	86.77	112.97	151.85	84.69	148.22
10.30	73.88	98.95	129.28	173.17	106.95	187.16
11.80	83.21	111.14	145.61	194.49	122.02	213.53
14.23	93.25	124.76	163.18	218.34	142.10	248.68
15.73	104.72	135.50	183.26	237.13	157.18	275.06
16.48	112.62	145.53	197.08	254.67	167.23	292.65

17.78	124.80	161.30	218.41	282.28	177.99	311.48
18.72	136.28	172.05	238.49	301.09	189.48	331.59
20.40	144.88	180.63	253.53	316.10	198.79	347.89
21.33	157.07	187.06	274.87	327.35	208.84	365.47
22.45	167.12	193.50	292.46	338.62	213.85	374.24
23.73	176.43	199.22	308.76	348.63	212.38	371.67
25.75	188.62	202.04	330.09	353.56	213.77	374.10
27.41	199.37	202.71	348.89	354.74	215.89	377.81
29.62	200.73	204.11	351.28	357.20	215.84	377.71
32.01	200.65	204.07	351.15	357.12	218.66	382.65
35.14	201.29	204.76	352.27	358.33	220.02	385.04
38.44	203.39	205.43	355.93	359.50	219.22	383.64
41.38	204.01	206.09	357.02	360.66	216.27	378.48
43.75	205.37	206.02	359.39	360.53	209.02	365.79
46.69	206.00	203.03	360.51	355.29	206.07	360.63
48.71	204.49	202.98	357.86	355.22	208.90	365.58
51.29	203.68	202.19	356.45	353.83	210.28	367.99
54.78	202.19	202.87	353.83	355.02	210.92	369.10
57.36	202.13	202.10	353.73	353.67	210.85	369.00
61.21	202.10	201.30	353.67	352.27	210.04	367.57

63.60	203.46	201.24	356.05	352.17	209.27	366.22
66.91	202.69	201.91	354.71	353.35	209.91	367.34
69.11	203.37	201.12	355.89	351.96	209.85	367.24
72.61	202.60	201.07	354.55	351.87	209.77	367.10
76.83	201.82	201.73	353.19	353.03	206.79	361.88
80.13	201.75	201.66	353.06	352.90	203.11	355.45
83.80	200.95	200.89	351.67	351.55	202.31	354.04
86.01	201.62	200.84	352.83	351.47	202.97	355.20
88.21	201.55	201.50	352.71	352.63	201.48	352.59
90.78	200.78	199.99	351.36	349.99	202.14	353.74
92.63	201.43	202.10	352.51	353.68	203.53	356.18
93.91	201.40	202.07	352.45	353.62	203.50	356.13
95.38	202.07	202.03	353.63	353.56	203.47	356.07
96.48	201.29	202.01	352.25	353.51	202.72	354.76

		Loading (kN)		Moment (kN.m)		Control Beam	
	Deflection (mm)	N4-1	N4-2	N4-1	N4-2	Load (kN)	Moment (kN.m)
Mean	42.02	154.95	164.63	271.16	288.10	172.62	302.08
STDEV	31.21	67.19	61.66	117.57	107.90	63.99	111.98
COV	0.74	0.43	0.37	0.43	0.37	0.37	0.37
MAX	96.48	206.00	206.09	360.51	360.66	220.02	385.04

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
385.04	360.58	0.11	0.00

N5 Series

Overall calculation

	Loading (kN)		Moment (kN.m)		Control Beam	
Deflection (mm)	N5-1	N5-2	N5-1	N5-2	Load (kN)	Moment (kN.m)
0.00	0.00	0.00	c	0.00	0.00	0.00
0.94	15.15	12.97	26.51	22.70	14.44	25.26
1.88	23.77	22.33	41.60	39.08	25.97	45.45
3.37	35.28	32.41	61.74	56.72	38.94	68.15
5.04	44.65	41.75	78.14	73.07	51.90	90.83
6.35	51.85	49.66	90.73	86.90	63.43	111.00
7.09	61.20	56.83	107.11	99.45	72.08	126.14
6.92	69.84	65.48	122.22	114.58	81.48	142.60
9.15	84.23	74.82	147.40	130.93	95.87	167.78
10.08	99.36	78.43	173.87	137.25	105.24	184.18
11.75	114.46	86.33	200.31	151.08	113.15	198.00
13.06	130.29	96.42	228.01	168.73	125.40	219.44
14.36	143.26	104.32	250.71	182.55	138.37	242.14
16.41	161.97	112.23	283.44	196.40	153.49	268.60

17.71	174.92	123.02	306.11	215.29	164.29	287.51
19.76	188.58	132.38	330.01	231.66	176.52	308.91
21.25	190.69	137.41	333.71	240.46	189.49	331.60
22.73	192.76	144.61	337.32	253.07	195.22	341.64
24.57	193.41	152.51	338.47	266.90	194.45	340.28
27.34	194.76	157.55	340.83	275.71	197.98	346.46
28.81	191.78	167.62	335.61	293.34	194.32	340.06
32.50	190.21	180.58	332.87	316.01	198.54	347.45
36.74	188.69	183.39	330.20	320.93	197.69	345.96
40.25	187.89	185.46	328.81	324.55	199.03	348.31
43.75	187.77	186.80	328.61	326.89	198.93	348.13
49.64	187.66	189.59	328.41	331.78	194.41	340.22
52.21	187.55	189.50	328.22	331.62	188.55	329.97
54.23	186.71	187.20	326.74	327.59	178.37	312.15
56.81	187.32	187.06	327.81	327.35	180.46	315.81
60.32	187.95	187.64	328.92	328.36	181.80	318.16
64.00	190.71	188.21	333.75	329.38	183.14	320.49
68.43	187.75	185.25	328.57	324.19	184.45	322.79
71.57	183.36	184.44	320.88	322.78	187.97	328.95
73.05	182.58	189.45	319.52	331.54	190.82	333.93

76.00	183.98	184.96	321.97	323.68	190.73	333.78
78.39	184.66	186.30	323.16	326.02	187.04	327.32
80.78	184.63	181.89	323.10	318.30	183.36	320.87
83.36	183.85	183.24	321.73	320.67	182.56	319.47
88.34	183.78	183.87	321.62	321.77	183.85	321.74
92.21	183.02	183.08	320.29	320.40	183.73	321.53
93.68	183.70	182.97	321.47	320.19	183.69	321.46

		Loading (kN)		Moment (kN.m)		Control Beam	
	Deflection (mm)	N5-1	N5-2	N5-1	N5-2	Load (kN)	Moment (kN.m)
Mean	38.167	148.439	135.608	266.262	237.314	150.028	262.550
STDEV	29.970	61.439	60.978	100.415	106.711	59.984	104.972
COV	0.785	0.414	0.450	0.377	0.450	0.400	0.400
MAX	93.683	194.758	189.587	340.827	331.777	199.034	348.310

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
348.31	336.30	106.94	0.32

H4 Series

Overall calculation

Deflection (mm)	Loading (kN)		Moment (kN.m)		Control Beam	
	H4-1	H4-2	H4-1	H4-2	Load (kN)	Moment (kN.m)
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.37	11.77	13.84	20.60	24.21	15.23	26.66
0.57	21.45	29.04	37.54	50.82	29.09	50.90
1.47	36.64	40.81	64.12	71.41	45.69	79.96
2.55	48.40	53.24	84.70	93.17	58.14	101.74
3.63	56.69	65.68	99.21	114.94	71.97	125.95
5.07	64.30	78.82	112.52	137.93	87.18	152.57
6.87	80.20	91.93	140.35	160.87	105.85	185.23
7.78	90.55	107.11	158.47	187.44	122.45	214.29
9.57	99.54	118.86	174.20	208.00	140.43	245.74
11.02	109.23	127.15	191.16	222.51	158.41	277.21
12.45	118.20	143.05	206.85	250.34	172.92	302.61
13.53	127.88	154.79	223.79	270.88	186.06	325.61
14.97	136.88	167.22	239.53	292.64	204.04	357.07

17.30	145.16	178.27	254.03	311.97	215.77	377.59
19.61	155.53	188.60	272.17	330.06	217.10	379.92
23.16	165.89	195.48	290.30	342.09	221.17	387.05
26.00	172.80	202.34	302.41	354.10	224.57	393.00
29.91	180.39	200.18	315.69	350.32	226.56	396.48
32.76	187.99	200.11	328.99	350.19	229.27	401.22
37.02	194.90	200.00	341.08	349.99	233.33	408.32
41.28	196.93	200.61	344.62	351.08	233.92	409.36
44.48	199.64	201.21	349.38	352.12	235.92	412.87
47.68	202.33	201.12	354.07	351.97	239.31	418.80
50.52	205.75	201.73	360.07	353.03	241.33	422.32
53.90	205.68	203.05	359.94	355.33	244.02	427.04
58.69	207.00	204.35	362.25	357.62	246.68	431.69
63.31	207.62	203.58	363.34	356.27	248.65	435.14
66.33	208.96	203.51	365.68	356.15	251.35	439.87
69.53	212.35	204.85	371.61	358.49	253.36	443.38
73.44	214.35	205.49	375.12	359.60	255.35	446.86
78.59	216.32	204.74	378.56	358.30	258.00	451.50
81.96	219.70	204.71	384.48	358.24	260.69	456.21
87.29	223.06	206.03	390.36	360.55	263.34	460.85

89.77	226.44	208.07	396.27	364.12	260.51	455.90
91.19	229.11	210.03	400.94	367.55	255.63	447.35
93.67	229.73	210.63	402.02	368.61	249.34	436.34
92.58	230.99	210.53	404.23	368.43	229.96	402.44

		Loading (kN)		Moment (kN.m)		Control Beam	
	Deflection (mm)	H4-1	H4-2	H4-1	H4-2	Load (kN)	Moment (kN.m)
Mean	38.42	153.69	158.97	268.96	278.19	189.28	331.24
STDEV	31.97	71.21	65.61	124.62	114.82	80.42	140.73
COV	0.83	0.46	0.41	0.46	0.41	0.42	0.42
MAX	93.67	230.99	210.63	404.23	368.61	263.34	460.85

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
460.85	386.33	25.19	0.07

H5 Series

Overall calculation

	Loading (kN)		Moment (kN.m)		Control Beam	
Deflection (mm)	H5-1	H5-2	H5-1	H5-2	Load (kN)	Moment (kN.m)
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.92	16.12	14.70	28.21	25.73	14.03	24.56
1.14	30.13	30.08	52.73	52.64	34.40	60.21
1.71	41.34	39.86	72.34	69.76	50.55	88.46
3.89	55.35	52.45	96.86	91.79	68.06	119.11
5.18	67.27	66.43	117.72	116.26	83.49	146.11
6.28	79.17	83.22	138.55	145.64	97.52	170.65
7.39	87.57	101.42	153.26	177.48	115.05	201.34
8.67	98.08	117.50	171.64	205.63	127.67	223.42
9.96	112.79	131.50	197.38	230.12	141.69	247.96
11.60	126.80	139.17	221.90	243.54	155.70	272.48
12.71	136.60	145.44	239.05	254.53	173.24	303.18
14.53	148.51	148.89	259.89	260.56	187.25	327.69
16.72	162.51	148.12	284.39	259.21	209.68	366.94

19.24	179.32	148.75	313.81	260.31	212.43	371.76
23.02	187.02	150.78	327.28	263.86	215.16	376.52
25.90	189.79	152.11	332.14	266.19	217.90	381.32
30.22	186.21	145.73	325.86	255.03	222.72	389.75
32.92	183.35	141.44	320.86	247.53	224.76	393.33
37.59	184.69	138.57	323.21	242.49	226.76	396.83
41.73	184.63	137.79	323.10	241.13	231.58	405.26
46.05	185.30	139.10	324.27	243.43	233.59	408.78
48.75	185.97	145.37	325.45	254.39	234.93	411.12
52.16	186.62	145.98	326.59	255.47	237.66	415.90
55.76	186.59	142.36	326.53	249.14	240.38	420.67
59.90	187.26	138.07	327.71	241.63	244.50	427.88
64.76	187.23	134.50	327.65	235.37	247.20	432.60
68.71	188.61	135.84	330.07	237.72	251.32	439.81
72.31	189.27	135.79	331.22	237.62	253.35	443.36
74.65	189.24	135.72	331.17	237.51	254.70	445.72
76.81	189.91	135.68	332.35	237.45	256.05	448.09
79.32	190.56	136.34	333.48	238.59	255.99	447.99
79.48	191.90	136.96	335.82	239.69	241.23	422.16
80.17	191.83	137.61	335.70	240.81	229.98	402.46

81.95	193.86	137.54	339.26	240.70	220.10	385.17

		Loading (kN)		Moment (kN.m)		Control Beam	
	Deflection (mm)	H5-1	H5-2	H5-1	H5-2	Load (kN)	Moment (kN.m)
Mean	35.77	145.75	119.17	255.07	208.54	183.16	320.53
STDEV	28.86	60.76	42.48	106.33	74.34	77.76	136.08
COV	0.81	0.42	0.36	0.42	0.36	0.42	0.42
MAX	81.95	193.86	152.11	339.26	266.19	256.05	448.09

Inputs for the code:

	Mtot (kN.m)		
Mn (kN.m)	Mean	STD	COV
448.09	302.73	51.67	0.17

Appendix B

Reliability Analysis Code

```
import matplotlib.pyplot as plt
import numpy as np
import scipy.stats
import statistics
from statistics import stdev

phee_list = []
phee_start = 0.01
phee_steps = 0.01
phee_end = 1
coef = int(phee_end/phee_steps)

def lower_bound_CI (data, confidence=0.95):
    a = 1.0 * np.array(data)
    n = len(a)
    m, se = np.mean(a), scipy.stats.sem(a)
    h = se * scipy.stats.t.ppf((1 + confidence) / 2., n-1)
    return m-h

def upper_bound_CI (data, confidence=0.95):
    a = 1.0 * np.array(data)
    n = len(a)
    m, se = np.mean(a), scipy.stats.sem(a)
    h = se * scipy.stats.t.ppf((1 + confidence) / 2., n-1)
    return m+h

#from scipy.stat import lognormal

Beams = input('Please enter number of beams:')
try:
    Beams = int(Beams)
```

```
except:
    print('Please enter an integer number')

for beam in range(Beams):
    print('Enter average for Mtot for beam #', (beam+1),':')
    mu = float(input())
    print('Enter StDev for Mtot for beam #', (beam+1),':')
    sigma = float(input())
    #mu, sigma = 260.9876, 0.2853
    Mtot = np.random.lognormal(mu,sigma,1000000)
    #Mtot = lognormal.cdf(1000000,mu,sigma)
    Mtot_list = Mtot.tolist()

    print('Please enter beam #', (beam+1), 'moment capacity average:')
    Ru = float(input())
    cov = 0.1
    StDev = cov * Ru



    check = False

    for i in range(int(phee_start*coef), int(phee_end*coef)+1):
        phee = i / coef
        Mn = np.random.lognormal((Ru*phee),(StDev*phee),1000000)
        #Mn = lognormal.cdf(1000000,(Ru*phee),(StDev*phee))
        Mn_list = Mn.tolist()

        if lower_bound_CI(Mn_list) < upper_bound_CI(Mtot_list):
            continue
        else:
            check = True
```

```
            print('For beam #',(beam+1), 'Mtot=', upper_bound_CI(Mtot_list), 'phee <=', phee,'everything will be OK!\n\n')
            phee_list.append(phee)
            break


        if check == False:
            print("the Moment Capacity for beam #", (beam+1),"is too low to endure the load")

    print('Minimun phee is', min(phee_list))
    #for number in range(len(phee_list)):
            #    normal = (phee_list- statistics.mean(phee_list))/stdev(phee_list)
    print("Target Reliability", 1-(len(phee_list)/1000000))


    import numpy as np
    from scipy.stats import norm
    import matplotlib.pyplot as plt


    # Generate some data for this demonstration.
    data = norm.rvs(0.844, 0.414 , size=500)

    # Fit a normal distribution to the data:
    mu, std = norm.fit(data)

    # Plot the histogram.
    plt.hist(data, bins=25, density=True, alpha=0.6, color='g')

    # Plot the PDF.
    xmin, xmax = plt.xlim()
```

```
x = np.linspace(xmin, xmax, 100)
p = norm.pdf(x, mu, std)
plt.plot(x, p, 'k', linewidth=2)
title = "Fit results: mu = %.2f,  std = %.2f" % (mu, std)
plt.title(title)

plt.show()
```

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