STOCHASTIC EVALUATION OF OFFSHORE CARBON FIBRE REINFORCED CONCRETE PLATFORMS ON ALUMINUM GIRDERS

By

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DECLARATION

I hereby declare that the work in this thesis '***Stochastic Evaluation of Offshore Carbon Fibre Reinforced Concrete platforms on Aluminum Girders***' is my research work and has been composed by me. It has not been presented in any previous work for the award of any degree. All sources of information utilized in this thesis that are not part of my conception are specifically acknowledged by means of references.

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CERTIFICATION

This project thesis '***Stochastic Evaluation of Offshore Carbon Fibre Reinforced Concrete platforms on Aluminum Girders***' byOlugbenga SamuelAbejide, has been read and approved as meeting the partial requirement of the Post graduate school of Ahmadu Bello University, Zaria, for the award of the Degree of Master of Science (M.Sc.) in Civil Engineering.

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α	-	Load ratio
$\alpha_1\beta_1$	-	Stress block factors for concrete based on CSA A23.3-94
ϕ	-	Risk of failure
A	-	Cross sectional area
A_{frp}	-	Cross sectional area of FRP reinforcement, mm^2
A_{frpu}	-	Cross sectional area of FRP reinforcement for balanced conditions, mm^2
β	-	Reliability index
b	-	Width of compression face of member, mm
b_w	-	Width of web, mm
C	-	Resultant of compressive stresses in concrete, N
c	-	Depth of neutral axis, mm
d	-	Effective depth, mm
DD	-	Dead load
ε_c	-	Strain in concrete
ε_{cu}	-	Ultimate strain in concrete in compression
ε_{frp}	-	Strain in FRP
E	-	Expected value
Efrp	-	Modulus of elasticity of FRP, MPa
f'_{ck}	-	Compressive strength of concrete, MPa
f_{frp}	-	Stress in FRP, MPa
f_{frpu}	-	Ultimate tensile strength of FRP, MPa
f_R	-	Stochastic variable for resistance parameter
f_S	-	Stochastic variable for load parameter
f_k	-	Characteristic stress capacity

f_t	-	feet
Gr	-	Gramme
GPa	-	Giga pascal
$G(x)$	-	Limit State equation
IL	-	Imposed load
Ƙ	-	Load carrying capacity
kg	-	Kilogramme
kN	-	Kilo Newton
kPa	-	Kilo pascal
l	-	Span of deck
LL	-	Live load
l_s	-	lengthofastiffenerbetween supports
M	-	Safety margin
M_R	-	Safety margin for resistance parameter
M_S	-	Safety margin for load effect parameter
Mpa	-	Mega pascal
M_R	-	Resistance moment
π	-	Pie constant
ρ_{frp}	-	Reinforcement ratio
ρ_{frpb}	-	Balanced reinforcement ratio
P_f	-	Probability of Failure
φ_c	-	Material resistance factor for concrete
φ_{frp}	-	Material resistance factor for FRP
Q_k	-	Live load factor
R	-	Resistance parameter
S	-	Load effect parameter

T	-	Internal force due to tension in FRP reinforcement, N
ϋ	-	Poison ratio
w	-	Uniformly distributed load
W_u	-	Ultimate load
γ_m	-	Partial coefficient for loads variable
γ_n	-	Partial coefficient for material variable
λ	-	Bias factor

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ABSTRACT

A stochastic evaluation of the performance of Carbon Fibre Offshore Plastics (CFRP) offshore platform consideringsubmerged and partially submerged environmental conditions wasanalyzed usingSwedish code,Boverket (2004). A Probability-based analysis using First Order Reliability Method (FORM) was used to determine the safety index of the deck considering varied load ratios, effective depths of the deck, and ultimate strength of Fibre Reinforced Plastics (FRP) tendons. The results generated from FORM indicates that the theoretical framework for risk assessment based on the Joint Committee for Structural Safety JCSS (2003) showed that the maximum safety index of the CFRP deck was shown to be 3.49 which is higher than the limit set by the JCSS (2003) code. Hence the deck can adequately transmit the given loading conditions when designed in accordance with Boverket (2004). Also the resultsof the Finite Elementanalysis carried out on the deck showed that the von-Mises stress was within acceptable limits, implying that the resisting moment of the CFRP deck was adequate. Hence, it is shown that the CFRP deck can be used in marine environment with increasing tidal loading as the CFRP wasalso able to resist failure due to compression. The flexural as well as shearing resistance are also within safety limits; and is about 500% greater than that of a steel reinforced concrete platform.However considering the serviceability limit state of deflection, the CFRP platforms did not show noticeable deformation in the geometry of the deck from the finite element analysis. The imposed load that can be sustained on a 150mm thick CFRP deck is $20kN/m^2$; while that of 200mm thick CFRP deck is $30kN/m^2$

CHAPTER ONE

INTRODUCTION

1.1 General

Corrosion is a major problem on reinforcedconcrete structures especially in the case of macrocell formation, because it can cause local loss of the reinforcement cross-section inconjunction with subsequent cracking and spalling of concrete cover in the structure. With increasing deterioration,the serviceability will be impaired and the load bearing capacity decreases. The inspectionand maintenance strategies to detect such damages can be costly and economicplanning is mandatory. In off-shore structures, structural components are built to be embeddedinwater as in the case of harbours, oil rig platforms just to mention a few. It is however essential that proper design to safely carry the imposed loadingsbe considered. Mostimportantly, design for the durability and resistance to: chloride effect, salty water, de-icing salt, freeze thaw etc. must be thoroughly considered (Humphrey, 2003).

Once corrosion gets started due to chloride ingress, anodic areas can be detected throughpotential mapping. Potential mapping provides two-dimensional information about a structure.This kind of information can be used for a spatial evaluation of corroding areas. It has to be considered that potential fields are influenced by several parameters such as concretecover and resistivity, which always will have an effect on the spatial variability.

The potential consequences of the corrosion problem can be summed up in the continuous reduction in strength, stiffness, durability and designed life time of the concrete structural elements reinforced with conventional steel. Considerable percentages of many national budgets are assigned either for innovative research works that can come up with radical solutions including corrosion problem or for repair, strengthening and in some cases reconstruction of damaged concrete structures (Humphrey, 2003).

The increasing number of concrete structures exhibiting unacceptable levels of deterioration,particularly in the marine environment has attracted widespread attention in recent years. Bridge engineers have had limited success in the past in combating these problems associated with the deterioration of bridge decks. The application of coatings and other protective systems to limit the corrosion effects of chlorides have yielded less than desired results (O' Connor, 1995). Corrosion is manifested in two primary forms: cracking and spalling of cover concrete due to the formation of expansive corrosion products at the reinforcement and local pitting at the anode which reduces the cross-sectional area of the bar (Makenzie,2001). However, high strength FRP tendons with definite properties is analysed and checked for its performance in a corrosive environment.

Concrete structures exposed to severe conditions of marine environment can be affected by three types of deterioration mechanism (Mehta, 1980; 1988; 1991 and 1996), namely,physical(such as freezing and thawing, wetting and drying and abrasion),chemical attack andchloride induced corrosion.

Aluminiumon the other hand, holds considerable promise to strength due to its ease of manufacturing and proven corrosion resistance. Not only can the metal survive harsh environments, it can at the same time do so without any protective coating (Davis, 1993). Aluminium decks as used in this thesis should not only be durable, but much lighter in weight than a conventional concrete deck. FibreReinforced Plasticcellular decks are modular systems that are light yet strong enough for any legal or permit load.They are relatively easy to install, and can be done in a few days instead of months. They havethe potential to last much longer than other types of deck because they are corrosion-resistant (Lou et al., 2011).

As will be seen in the course of this research, an aggressive environment is proposed and the performance of an aliminium girder of 10m span will be analysed.

In the present and common design codes, BS 8110 (1985,1997), CP 110 (1972) and ACI-318 (2002) as well as Swedish design codes, durability requirement for concrete structures are largely based on the conventional method of specifying arbitrarily certain limiting values e.g. concrete grade, minimum cement content, maximum water-cement ratio, cover thickness and maximum structural crack width (Kabir,2007). This is also the case with EC2 (2008). Based on substantial data available from field performance, exposure trials and laboratory tests on concrete, many researchers are convinced that the current code requirement do not provide adequate resistance to chlorides, even when properly implemented. The deemed-to-satisfy rule for concrete "durability" in the present codes can be challenged (Vandanda and Hosain, 1992).

It is with this notion that CFRP reinforced concrete deck on aluminium girders in offshore is proposed to evaluate its performance for use in marine (Chloride) and other aggressive environments.

1.2 Problem Statement and Justification of Study

1.2.1 Problem Statement

The reaction between concrete members and seawater in offshore over time can lead to corrosion damage of the reinforcement needed to provide strength to the structural member; thus a reliable resistance to the failure modes with which such members fail during their design lives need be properly investigated.

1.2.2 Justification of Study

The time-rate deterioration of structural members over the years has been a problem that still needs to be properly investigated especially when the said structural members are in use during their designed service life span. The need for a probabilistic check on thestructural strength durability and efficiency while in service must be thoroughly defined in order to ascertain the time rate of failure, cause of failure and design life span of the member in question. The concept of service life prediction for concrete structures is becoming an area of increasing interest for engineers. Therefore, a good understanding of the concept and its application in structural design is essential to ensure that optimum concrete performance is achieved before a costly repair to the structure becomes necessary (Humphery, 2003). It is on this basis that the durability of concrete in service conditions is a very important criterion to the safety of concrete structures. It is with this concept that this work is primarily generated in order to determine a stochastic as well as deterministic evaluation on the failure of cellular CFRP reinforced concrete platforms on aluminum girders in offshore or bridge environment.

1.3 Aim and Objectives

1.3.1 Aim

The aim of this work is to stochastically evaluate the performance of CFRP offshore platforms on aluminium girders.

1.3.2 Objectives

The objectives of the study are as follows:

(i) To stochasticallyevaluate the formulations of performance and safety criteria of the Aluminum and cellular CFRP reinforced concrete platforms over the use of steel reinforced concrete in an aggressive environment using the requirements of design codes: ACI-318 (2002) andEC2 (2008).

(ii) To generate reliable structural safety limit functions of submerged and partially submerged decks or platforms in aggressive conditions.

(iii) To carry out finite element analysis on thecellular carbon reinforced fibre deck.

(iv) To carry out reliability analysis of the designed carbon fibre reinforced deck.

1.4 Scope and Limitations

1.4.1 Scope

The design of the cellular CFRP reinforced concrete slab will be made at varying depth thicknesses when reacted with varied corrosion loading. However the girder section of the slab platform will equally be evaluated using the Load Resistance Factor Design (LRFD). A specified design model will be defined and results obtained so as to generate the structural safety indices of the model.

The use of Finite Element Analysis and First Order Reliability Methodis considered namely ABAQUS and FORM (Gollwitzer, et al, 1988) respectively to check the structural safety in a stochastic environment. This will show the confidence on the structural performance of the type of deck and girder system proposed.

1.4.2 Limitations

The study has the following limitations:

1. Lack of relevant data regarding many parameters used in durability design for CFRP, aluminium and concrete. Therefore, material properties data required for analysis are rarely available.

2. Attempts to improve the ductility of CFRP have been with little or no success (Michael, 2006, Grace et al 1998).

3. CFRP bars when loaded in tension, exhibit linear stress-strain behaviour up to rupture (Bergstrom, 2006; Mackenzie, 2001).

CHAPTER TWO

LITERATURE REVIEW

2.1 Offshore Platforms and Corrosion effect

Offshore platforms are structures constructed in marine environments, usually for the production and transmission of electricity, oil, gas and other resources. Offshore platforms are also referred toas oilrig platforms. An oilrig is a large structure with facilities to drill well, extract and process oil and natural gas, and temporarily store product until it can be brought to shore for refining and marketing in many cases. The platforms contain facilities to house the workforce as well. The platforms may be fixed to the ocean floor, consisting of an artificial island or may float. Construction in the offshore environment is a difficult and dangerous activity. Construction and pre-commissioning is typically performed as much as possible on land or onshore areas. To optimize the costs and risks of installing large offshore platforms, different construction strategies have been developed; such as full construction of the offshore facilities inshore and tow the installation for site floating on its own buoyancy, constructed facility onshore and then lifted using crane vessels into place onto the platform (Phillip, 1993).

Concrete offshore platforms are mostly used in the petroleum industry as drilling, extraction or storage unit for crude oil or natural gas. Those large structures house machinery and equipment needed to drill and extract oil and gas. Several conceptual studies have shown recently that concrete structures for offshore and wind turbines are very competitive when compared to common steel structures, especially for larger depths (Phillip, 1993).

Concrete structures exposed to marine environment have been found to suffer mainly from corrosion of the reinforcing steel (Humphery, 2003). It is necessary for engineers to understand the importance and mechanisms of chloride induced corrosion of steel in concrete. The effect of the quality of concrete on the resistance to chloride penetration, chloride threshold and corrosion rate of the reinforcing steel are critical in determining the service life of structures in the environment.

Corrosion of reinforcing steel in bridge decks can be initiated by one of two modes,chloride-induced corrosion or carbonation-induced corrosion. To understand thedifferent modes of corrosion and the reasons for corrosion initiation, one must firstunderstand the nature of steel in concrete. Steel when placed in an alkaline environmentsuch as concrete, develops pore waterand a passive layer of corrosion products. Thispassive layer is composed of iron oxides or hydroxides and is very dense. Over time thispassive layer will reach a thickness sufficient to protect the base metal and the corrosionrate will for all practical purposes be equal to zero. As long as the passive layer remainsintact active corrosion will not initiate, however, if the reinforcing steel is depassivated,active corrosion can initiate and continue to propagate.The corrosion of reinforcing steel in concrete is a complex electrochemical process**(**Mackenzie, 1989**)**. Inorder for a corrosion cell to form, there must be an anode, a cathode, an electricalconnection between the two, and an electrolyte. For reinforcing steel in concrete, both theanodic and cathodic areas may be present on the surface of an individual bar or they maybe on different bars. The electrical connection is provided by the reinforcement itself and the saturated or partially-saturated concrete completes the corrosion cell by serving as anelectrolyte. Corrosion cells where the anode and cathode are directly adjacent to oneanother are referred to as micro-cells whereas cells with the anode and cathode separatedby some distance are considered macro-cells.The anode is the site of active corrosion where the dissolution of iron and formation ofcorrosion products occurs and the cathode is the site where oxygen is reduced to formhydroxyl ions(Broomfield, 1997).

The primary concern with corrosion of reinforcing steel in bridge decks is not the loss ofcross-sectional area because bridge decks are designed in such a way that the amount ofsteel used typically far exceeds that which is required for strength. The problem mostassociated with the corrosion of reinforcement in bridge decks is the durability of thesurrounding concrete. As corrosion progresses and iron reacts to form ferric oxides asignificant volume change takes place.

The volume change (200-1000%) associatedwith the corrosion process results in a buildup of pressure at the concrete-reinforcementinterface, which ultimately results in the cracking, spalling, and delamination of theconcrete cover, (Broomfield, 1997).

2.2 Fibre Reinforced Polymeric Materials

FibreReinforced Polymeric (FRP)materials may consist of glass, graphite or carbon,aramid, boron, silicon carbide, natural fibres, etc. held together in a structural unitwith a binder or matrix material and combined with fillers for mechanical performance or cost benefits. The binder or matrix material for FRP is either a thermosetor thermoplastic. Thermosets use polymer chains that cross-link and therefore do notmelt at high temperatures. Thermoplastics, on the other hand, use polymer chainsthat do not cross-link allowing them to melt and harden again when cooled. Typicalthermosets are epoxies, polyester, or phenolic. Typical thermoplastics are polyamide,polysulfone, polyetheretherketone (PEEK), or Polyphenylene sulfide.

Types of fibre reinforced composites include continuous, woven, chopped, and hybrid composites. Hybrid composites consist of mixed fibre types or fibre geometries.Continuous composites consist of continuous fibres oriented in individual layers orlaminae and bonded together to form a laminate. Fabrication processes for FRPtypically include open molds, autoclave, compression moulding, filament winding,pultrusion, reinforced reaction injection molding, thermoplastic molding, resin transfer molding, and structural reaction injection molding. An autoclave is a heatedpressure vessel which takes a laminate through a temperature and pressure curingprogram. Prepreg is typically used for autoclaved laminates. Prepreg is a type ofprecoatedfibre with polymer resin. Achieving void contents of 0.1% is typical forautoclaved laminates using prepreg. Pultrusion is a manufacturing process in whichunidirectional filaments are impregnated in resin and pulled through a heated dieto produce long prismatic structural components. Pultrusion and autoclaving areused for fabricating the glass, carbon, and hybrid jute-glass fibre reinforced polymericmaterials used.

2.3 Factors Affecting Marine Concrete Durability

Deterioration of reinforced concrete structures in marine environments is generally associated with external agents such as chloride that penetrates into concrete causing damage. Using the premise that the potential durability of reinforced concrete is determined by the protection provided by the concretecover, a number of factors affecting durability may be defined. These include concrete type, concrete cover depth to reinforcement; site practice and severity of exposure (Humphery, 2003).

1. **Concrete type:** The type of concrete used to protect reinforcement has a major influence on durability since the material controls the rate at which aggressive agents move through the concretecover. Current codes of practice make allowance for the improved chloride resistance of higher grade concrete but largely control transport properties of the material, while largely ignoring chemical effects. Chlorides ingress into concrete is not only determined by the permeability of the pore system but also by interactions between the material and the diffusant that depletes the concentration and constricts the pore structure. Concrete containing fly ash and slag have been shown to have exceptional chloride binding characteristics and produce material of high chloride resistance (Humphery, 2003)..
2. **Cover to reinforcement**: The potential of reinforced concrete is greatly enhanced if adequate cover to reinforcement is specified and achieved on site. For sufficient protection of fibres under marine conditions, covers should be in the region of 50 to 75mm. Reduced cover is risky even when using high quality concrete since defects such as cracks and voids may provide a low resistance path to the reinforcement.

Increasing cover to depths beyond 75mm may however result in excessive surface crack widths and is often not practically possible.

3. **Site Practice**: poor site practice, particularly with regard to placing, compaction and curing of concrete may negate the benefits of good design and material selection. Research has established that the value of good site practice such as active moist curing improves the near-surface properties of concrete (Mackenzie, 1989). Specifications have been proposed to control these site activities, but unfortunately adequate supervision and suitable methods to monitor compliance have not been implemented on site. The inability to ensure consistent quality of concrete on site is a major reason for the continued prevalence of concrete durability problems, (Mackenzie, 1989).

4. **Severity of exposure**: The severity of concrete exposure varies considerably depending on factors such as climate, location relative to the sea and structural considerations. Current codes of practice provide limited guidance about exposure conditions and generally define only two concrete categories: extreme exposure for concrete subjected to full abrasive action of the sea, and very severe exposure for concrete subjected to spray or mild abrasive/wave action. The wide variations of exposure in the marine spray zone are not adequately defined by these categories. This is particularly problematic since most marine concrete structures are located in the spray zone. Given the range of marine conditions, a more comprehensive and rationally structured system for defining the severity of exposure needs to be formulated. (Cao, 1998; Mackenzie, 2001).

2.4 Carbon Fibre Reinforced Plastic (CFRP)

Carbon FibreReinforced Polymers or carbon fibre reinforced plastic (CFRP) is very strong and light fibre reinforced polymers which contain carbon fibres. The polymer is most often epoxy but other polymers such as polyester,vinyl ester or nylon are sometimes used.

The composites of FRP may contain other fibres such as Kevlar, Aluminum or glass fibres as well as carbon fibre. The strongest and most expensive of these additives are carbon-nanotubes,and they are contained in some primary polymer baseball bats, car parts and even golf clubs where they are economically viable. Carbon fibre relatively has many applications in aerospace and automobile body parts. The compound is also used in sailboats, modern bicycles, motor cycles and ship members where its high strength-to-weight ratio and good rigidity is of importance. Improved manufacturing techniques are reducing the costs and time to manufacture, making it increasinglycommon in small consumer goods such as laptops, tripods, fishing rods, helmets, etc. The primary element of CFRP is a fibre. From this fibre, a unidirectional sheet is created. These sheets are layered onto each other in a quasi-isotopic layout, for example; 0, +60, -60, degrees relative to each other (Bayani, 1989).

Carbon fibre reinforced polymer is used extensively in high end automobile racing, aircraft design etc. Many super cars over the past few decades have incorporated CFRP extensively in their manufacture such as using it for their mono-coquechassis as well as other components (Nanni, 1993).

CFRP typically has a large impact on strength compared to reinforced concrete structures for flexure, but only to moderate the stiffness. This is because the material used in this application is typically very strong (3000MPa ultimate tensile strength, more than 10 times mild steel). As a consequence, only small cross sectional areas of the materials are used, small area of very high strength but moderate stiffness material will significantly increase strength (Yamasaki et al., 1993).

CFRP can also be used to enhance shear strength of reinforced concrete by wrapping fibres around the section to be strengthened. Wrapping around section such as bridge or building columns can also enhance ductility of the section, thereby greatly increasing the resistance to collapse under earthquake loading. Specialist ultra-high modulus CFRP with tensile modulus of 420GPa or more is one of the few practical methods of strengthening cast-iron beams. In typical use, it is bonded to the tensile flange of the section, both increasing the stiffness of the section and lowering the neutral axis, thus greatly reducing the maximum tensile stress in the cast iron when used as a replacement for steel. CFRP can be used as prestressing materials due to their high strength. The advantage of CFRP over steel as a prestressing material, namely its light weight, corrosion resistance, high specific stiffness, potential modular fabrication and installation that can lead to decreased field assembly time and traffic routing cost, should enable the material to be used for niche application such as in offshore environment (Humphrey, 2003).

Although, CFRP tendons are very costly compared to the conventional steel reinforcements; hence, its use in crucially essential areas under rupture over time. It is essential to adopt the AASHTO-LRFD (2010) method of design since the strength of the deck is not governed by flexure criteria. This will provide for a reduction in the slab or deck reinforcement; thereby prolong the life of the deck and reduction in total cost of construction, materials and labour.

2.5 Philosophy of Structural Reliability

Computer techniques of structural analysis have improved the accuracy of representing the actual behaviour of bridge components. Advanced programs (such as; ABAQUS, NASTRAN, ANSYS, SAP etc.), are available for linear and nonlinear analysis of complex structural systems. A dense element mesh allows for an accurate determination of strain/stress at almost any point in the structure. One major problem that remains is how to represent boundary conditions and material properties. For example, the actual support insitu is often different from an idealized type, and strength of material and modulus of elasticity can be different than what is assumed in design. The deterministic analysis is a useful tool, but there is need to include the randomness of parameters such as these (Nowak, 2004).

The study of structural reliability is concerned with the calculation and prediction of the probability of a limit state violation for engineered structures at any stage during their life. In particular, the study of structural safety is concerned with the violation of the ultimate or safety limit state for the structure.The "violation" of a limit state is the attainment of an undesirable condition for the structure, i.e. damage to a part of the structure or total collapse of the structure which could lead to loss of human lives (Melchers, 1987).

Society expects buildings, bridges and other structures to be designed with a reasonable safety level. In practice, these expectations are achieved by following code requirements by specifying design values for minimum strength, maximum allowable deflection and so on. Code requirements have evolved to include design criteria that take into account some of the sources of uncertainties in design. Such criteria are often referred to as reliability-based design criteria. (Ditlevsen and Madsen, 2005)

The reliability of a structure is its ability to fulfill its design purpose for some specified design lifetime. Reliability is often understood to equal the probability that a structure will not fail to perform its intended function. The term failure does not mean catastrophic failure but is used to indicate that the structure does not perform as desired. The reliability of a structure can be considered as a rational evaluation criterion. It provides a good basis for decision about repair, rehabilitation, or replacement (O'Connor, 1995). A structure is said to have failed when the nominal value of load exceeds the nominal value of load carrying capacity. But in most cases, a structure is a system of components, and failure of one component does not necessarily mean failure of the structural system. When a component reaches its ultimate capacity, it may continue to resist the load while loads are redistributed to other components. System reliability provides a methodology to establish the relationship between the reliability of an element and the reliability of the system. Reliability based design, which accounts for uncertainties in design variables can be used as an essential means for checking the consistency of existing codes, with the view of optimizing the code so as to produce more consistent and economic codes for a better design, (Ellingwood, 1978).

The probability of occurrence of an event such as a limit state violation is a numerical measure of the chance of its occurrence. This measure may either be obtained from the measurement of the long-term frequency of occurrence of the event for generally similar structures, or may be simply a subjective estimation of the numerical value. In practice, it is not usually possible to observe for a sufficiently long period of time hence, a combination of subjective estimation and frequency observations for structural components and properties is used to predict the probability of limit state violation for the structure as a whole (Thoft-Christensen and Baker, 1982).

Structural reliability with respect to some limit states is quantitatively expressed by a number on a suitable scale being related to a given time period (Augusti, et al, 1984). Taking for granted that the reliability evaluation is based on probabilistic modeling, the reliability measure scale is in one-to-one correspondence with the probability that the adverse event occurs within the considered time period (Ditlevsen and Madsen, 2005).

2.5.1 Reliability of CFRP Decks

A statistical review of FRP deck on steel girder was performed by Craig (1993). This was developed in an effort to rehabilitate three open-grate deck bridges, using the Innovative Bridge Research and Construction (IBRC), programme which included design considerations as regards selection of deck thickness, loadings, and wearing surface treatment.

2.6 Reliability of Aluminium Bridge Girders

Aluminium alloys in general structural use have excellent corrosion resistance, which is attributable to the protective oxide film which forms naturally on exposure to air. The film is usually invisible, relatively inert and adheres strongly to the metal surface. Once formed, it prevents further oxidation and reforms naturally if damaged. It is thus self-healing. The 5xxx and 6xxx series alloys will develop small pits when exposed to industrial pollution. A layer of corrosion product which inhibits further corrosion seals the pits and results in a dull grey weathered appearance for untreated aluminium. The 7xxx series alloys exhibits a layered form of corrosion rather than pitting, and is non-durable compared to other alloys of aluminium.

The oxide film on the aluminium alloy acts as a natural barrier and until this breaks down from acidic or alkaline moisture, or through abrasion, that the bi-metallic cell will activate. Thus corrosion between stainless steel and aluminium, which have a large potential difference, is non-existent in most environments as the contact is between two inert oxide layers. Connections between dissimilar metals that are subject to fretting or relative movement can sometimes corrode rapidly, as the protective oxide film is repeatedly worn away. Insulating the dissimilar metals with an inert non-absorbent barrier can prevent reaction (Dwight, 1999).

Aluminium is the third most abundant element in the earth's crust, occurring mostly as alumino-silicates. The abundance of raw material and ease of recycling are such that resource depletion will not be an issue. It is extracted by electrolysis of alumina from bauxite fused with cryolite. Extraction rates are good, with 4tons of bauxite producing 1tonne of aluminium. Various studieshave been carried out to consider ecological impacts by applying life-cycle analysis techniques, and comparing aluminium with other materials such as steel for structural components in buildings. Using the cumulative energy demand as a comparator, aluminium structures with an anodized or painted surface have slightly less of an impact than painted or galvanized steel, once recycling is taken into account. If the aluminium is left with no surface treatment, the difference becomes greater. The studies have generally assumed that the structural elements of the structure will not be repainted in their lifetime. Similar studies for bridgework should therefore show an even greater benefit from using aluminium. The electrolytic process used in a primary smelter is energy intensive, and it is not surprising that the majority of primary aluminium is produced using hydroelectric power. Current figures show that about 95% of aluminium used in the construction industry is recycled. Energy consumption in the recycling process is only about 5% of that used in producing new aluminium. Other advantages accrue from savings in fabrication, transport and handling due to the low self-weight and from labour-saving features that can be incorporated in extrusion design.

However; research into structural application of aluminium alloys in civil engineering structures is disappointingly sparse, and most future developments are likely to arise from advances in other applications, such as aerospace and transport industries that have different criteria to address. Traditionally, the use of castings has been discouraged for structural applications, as the quality and brittle characteristics of many castings have been unsuitable. The automotive and aerospace industries have developed the use of high-precision castings that have good ductility, and are increasingly using these in combination with purpose designed extrusions. Such methods are particularly appropriate for volume production. The technology is likely to be useful in civil engineering, if sufficient quantities can justify the development and tooling costs for any specific project or proprietary system.

But the development of material technology using fibre-reinforced aluminium and powder metallurgy promise materials that are stronger and stiffer than the current alloys in structural use. The increase in stiffness will be particularly relevant. Technology for joining materials is an area of research and development that transcends different industries quite well. Developments in friction stir welding and adhesive bonding over the past ten years have yet to become firmly established in the civil engineering industry, and are not covered in detail by the current design codes. They are however, well established in the manufacture of railway carriages and in military bridging (Siwowski, 2006; Tindall, 2008).

An extensive study has been carried out on the load distribution models among girders using various design parameters. The load distribution factor (LDF) is a function of many parameters, which includes member geometry, member stiffness as well as the nature of loading which could be varied amongst certain bridge model loading using design codes. Due to the vast and non-streamlined form of loading conditions, an ideal load distribution equation should include the major parameters that have practical effects on the load distribution (Cai, 2005). Based on this, Cai, (2005)proposed a new formula which was considered to be more rational and has more physical meaning than that used in the current LRFD codes, (Agboola, 2010).

2.7 Determination of Design Loads on Fibre Deck Structures

Recently, a draft proposed standard was prepared for the International Maritime Organisation (IMO), covering testing of fire endurance of loaded FibreReinforced Plastic (FRP) vessels structures. Thisreviewfocusedonanexaminationofdesignloads (i.e.,theloadingswhichareassumedtoactonastructurefor thepurposesofsizingthestructure'sscantlings).

Forthepurposesofthisreview,theterm"designload"wastakentomeantheassumedloadingthatisusedto determinethe minimumrequirements(e.g.,platingthicknessandstiffener spacingandcross-sectionconfiguration)ofavessel or deckstructure. Thedesignloadcanalsobeconsideredtobethemaximumloadthatastructurecanbeexpectedto carrywithoutriskingdamage.Asdiscussedbelow,availablesourcesdifferasto proceduresforcombiningvariouspossibleloadingconditionsin ordertodevelopspecificdesignloadvalues. Designloadsare oftenestablishedfora vessel or deckonanindividualbasis, takingintoaccounttheprobability,magnitudeandfrequencyof anassumedmaximumseastate,slammingorotherexpectedloading conditions.

Again,basedonavailablesources,thereappearsto benogenerally-acceptedmethodofdevelopingdesignloads,or theassociateddesignstressesandmarginsofsafety,which involvematerialstrengthpropertiesaswell (Charles, 1995). Toestablishtherequiredsizes or scantlings ofthestructure, itisnecessarytofirst determinethemaximumload imposed on it.

The major loadsimposedon a ship deckstructure or considerably an offshore platform can be conveniently divided into the following groups(Charles, 1995):

a.) Stillwater bending moment and shearing forces
b.) Wave-induced moments and shearing forces
c.) Springing and impulsive loads
d.) Thermal loads
e.) Dynamic loads i.e. Hydrodynamic pressures (Sloshing)
f.) Other loads such as lurching; docking; grounding; mooring; water current collision; imposed live loads due to weight of machineries; human activities; vessels; etc.

Insomedesignmethods,individualloadsaregroupedinto loadcategories.Oneof suchcategorymightincludetheloadsthat areassumedtoact onavessel'sstructurecontinuously(e.g., weightofcargoorstores,loadsduetoliquidsintanks,dead weightofstructure),andwhichmaythereforebeconsidered normaloperatingloads.Othercategoriesmightincludeloads assumedtooccuronlyunderunusualoperatingconditions(e.g., seaslaporslammingloadsinhighseastates),orloads resultingfromcasualtyconditionssuchasflooding. Eachoftheseunusualloadsisassumedtoactindependently(butconcurrentwiththenormaloperatingloads) , oneloadatatime.

2.7.1 Design load

Whenloadedstructuralspecimensaretestedforstructural performance,theappliedloadingsshouldatleastapproximatethe conditionsthatthestructureswillexperienceinservice.In ordertoestablishreasonableloadingconditions,several sourceswerereviewedto obtaininformationonthedesignloads typicallyusedfordesigningoffshore platforms as shown in Table 2.1.These sourcesincludeddocumentsrelatedtoCoastGuarddesign approval,classification,codes of practice,concretestructuredesignmanuals,navalarchitecturaltexts,technicalpapers,and AmericanBureauofShippingandseveralnavalarchitecturalfirms(Charles 1995).

Asa generalguideline,thedeflectionofpanels andstiffenerssubjectedto theloadsdiscussed previouslyshouldnotexceedthefollowing,where$l_s$is definedasthel engthofastiffenerbetween supportsortheminimumunsupportedspanofthepanel(Charles, 1995):

$$\left.\begin{array}{ll} \text{Bulkheads-floodingloads} & l_s/50 \\ \text{Decks-uniformloads} & l_s/100 \\ \text{Decks-footprintloads} & l_s/100 \end{array}\right\} \quad (2.1)$$

Table 2.1. StandardDesignLoadsfor DeckStructures

Descriptionof Structure	Type of Loading Represented	Recommended DesignLoad
ABSDecks (reinforced plasticvessels)	Cargoweight	540psf(2636kg/m^2 for "normal" cargoweight (Note1)(25.9kPa)
NAVSECDecks(navalsurface ships)		
Exterior		
	Liveload Iceandsnow Greenseas	250psf(Note2)(12.0kPa) 7.5psf(0.36kPa) Approx.12fthead (768psf)(36.8kPa)max fwd;4fthead(256psf) (12.2kPa)aft(Note3)
Interior (MainDeckandabove Note4) (BelowMain Deck) LivingSpaces	Liveload	75psf(3.6kPa)
Officesand controlspaces		100psf(4.8kPa)
(ShopSpaces)		150psf(7.2kPa)
(Storerooms)		200psf(9.6kPa)
		300psf(Note5), (14kPa)
ScottDecks(fibreglass boats)Exterior(yachtsand sailboats)		
(workboats)		
Interior(yachtsand sailboats)		125psf(Note6)(6.0kPa)
(workboats)	Total	2QQpsf, 96kPa)
KingslakeDecks(smallwarships)		
Exterior		50psf(" ")(24kPa) 100psf(" ")(48kPa)
Interior		
	Equipment weightplus waterhead	216psffwd,(10.3kPa) 144 psfaft,(6.89kPa)
	Equipmentand personnel	144psf(Note7)(6.89kPa

(Source: Charles, 1995)

The determination of realisticdesignloadsfor

bulkheadanddeckstructurescanbeacomplexprocess.Inordertoensurestructuraladequacy,thedesignermustconsidera numberofenvironmental,operationalandmaterialfactorsthat oftenvarygreatlyfromcaseto case.Forthisreason,itisreasonabletoassumestandardnumericalvaluesforoverall designloadsinactualpractice.

Therefore,themoststraightforwardmethodofdetermining theloadingtobeappliedtoastructureduringperformancetestingwouldbetorequirethatthestructuraldesigner providesthenecessarydesignloadinformation(e.g.,headin feet,uniformloadinginpoundsper squarefoot or other unit,magnitude, locationanddirectionofpointorconcentratedloadings,etc.) foreachspecificstructuralspecimentobetested.Ifsuchinformationisnotavailable,anditbecomes necessarytoestimatetestloadings,thefollowingvaluesare suggestedfordeckstructures as shown in Table 2.2 below(Charles, 1995):

Table 2.2 ApproximateWeightsofVariousDeckSystems.

DeckType	**Weight,excluding wearingsurface**	**Weight,including typicalwearing surface**
Reinforcedconcrete(88% ofdecks,perNBI12/08)	100-120 psf	100-120 psf
Exodermic	50-75 psf	50-75 psf
Opensteel grate	17-55 psf	17-55 psf
Filledsteel grate	70 -100 psf	70 -100 psf
Timber	22-30 psf	46-54 psf (assume2-inasphalt)
FRP	12-25 psf	16-29 psf (assume3/8-inpolymer concrete)
Hybrid (FRP andgrout)	~ 25 psf	~28-30 psf (assume¼-inpolymer concrete)
Notes:Usemanufacturers’weightsfordesign;theaboveweightsareapproximateranges. NBI= NationalBridgeInventory		

(Source: Charles, 1995)

2.8 Performance Criteria of Fibre Reinforced Plastics Components

The deck panels will be loaded with a specific and defined uniformly distributed load over a specified span not exceeding 10m and consequently increasing the rate of loading with time in other to ascertain the maximum load carrying capacity at which the FRP component can be subjected to. The choice of 10m span is to provide reliable design against deflection criteria.

The Ohio Department of Transportation specified the performance criteria for flexure, shear and deflection of FRP deck panels. The deflection limits for FRP deck panels are based on the deflection calculations limits for conventional reinforced concrete deck panels (Table 2.3), and they varied from *L*/596 to *L*/762 for single spans, and *L*/851 to *L*/1,097 for continuous span bridge deck panels, respectively (Alagusundaramoorthy et al., 2006).

Table 2.3 Deflection Limits of FRP Panels

Span L(mm)[a]	Clear span used for design (mm)	Deck thickness[b] (mm)	Applied service load[c] (kN)	Single span deflection[d] (*l*/k)[f]	Single span deflection[d]	Continuous span deflection (*l*/k)[f]	Continuous span deflection[e] (mm)
2,433	2,286	203	53.4	L/762	3.2	L/975	2.5
2,743	2,591	203	53.4	L/596	4.6	L/1,097	2.5
3,048	2,896	229	53.4	L/709	4.3	L/1,089	2.8
3,658	3,505	241	53.4	L/600	6.1	L/851	4.3

(Source: Ohio Department of Transportation).

a= Measured distance between centerline of the supports

b= Manufacturers are permitted to increase the depth of their decks within +12.7mm of the thickness shown for the 3,048 and 3,658mm span lengths.

c= Load is to be applied over 229mm x 559mm contact area.

d= Simple span values are to be used during testing to evaluate the FRP decks relative to an Rc deck [1in = 25.4mm (1kip = 4,4482 kN)].

f= *l*/k = deflection limit designation: L = span length as indicated in a,and k = deflection coefficient.

The flexurecriterion is based on the following:

1.) The maximum allowable strain is limited to 20% of the ultimate strain under service load of:

    U = LL+IL+DL (2.2)

    Where:U = Design Load, LL = Live load, IL= Impact load, and DL = Dead load

2.) The maximum allowable dead load strain is limited to 10% of the ultimate strain; this includes:2.9 kPa(60 psf) of future wearing surface.

3.) The maximum factored load of:

    U = 1.3 +1.67 = LL+IL+DL. (2.3a)

    Equivalent to 50% of ultimate load capacity of FRP deck panels;

4.) The maximum factored load of:

    U = 1.3 + 1.67 = LL+IL+DL. (2.3b)

    Equivalent to100% of ultimate load capacity for hybrid FRP concrete deck panels.

5.) Required strength Uto resist dead load D and live load L shall be at least equal to (ACI 318, 1995)

    U = 1.4DL+ 1.7LL (2.4)

The shear criterion is based on the following:

1.) The shear capacity shall be equal or greater than that of a corresponding reinforced concrete conventional deck panel. The shear capacity of the deck is 146 KN/m (10,000lb/ft).

2.) The maximum allowable shear at a factored load of:

$$U = 1.3 + 1.67 = LL+IL+DL \quad (2.5)$$

shall be equivalent to 45% of the ultimate shear load capacity for all non-hybrid FRP deck panels.

3.) The maximum allowable shear for a factored load of:

$$U = 1.3 + 1.67 = LL+IL+DL \quad (2.6)$$

shall be equivalent to 100% of the ultimate shear capacity for hybrid FRP concrete deck panels.

2.9 Performance Objective of the CFRP Deck

The expectations of the deck are as follows:

(a) Excellent Technical performance: The deck will sustain ultimate loads (Dead and Imposed Loads) and must be able to withstand occasional overloads without damage. Global deflection, local deflection and thermal distortion are to be kept small enough such that cracking and spalling does not occur; internal stresses and fatigue problems must be checked and avoided at the design of the joint connection points.

(b) Maintenance should be minimal: The wearing surface should stay bonded and not suffer excessive wear.

(c) The design life is set at 75 years per the American Association of State Highway and Transport Officials (AASHTO) and the Loads and Resistance Factor Design (LRFD) bridge design specification (AASHTO-LRFD, 2010).

(d) The deck system should be able to accommodate future widening or strengthening to accommodate heavier loads.

(e) The weight per square meter should be comparable to other light weight decking systems.

(f) Reasonably cost effective since the primary emphasis will be given to initial material costper square meter. A long service life with minimal maintenance requirements will considerably reduce the life cycle cost.

2.10 General Principles in Design of Girder Structures

In girder design, the maximum moment is necessary in the determination of the optimum girder section that will be adequate enough to sustain the load anticipated. There will however be a load transfer from the deck to the girder section. This may take the form of a complex behavior of load transfer from the deck or slab to the steel girder (Steel Bridge Design Handbook, 2005). The AASHTO LRFD (2010) bridge specification suggests many methods to analyze bridges, i.e. the finite element analysis, grillage analysis, and a load distribution factor (LDF) equation. This method is also employed in this work.

2.11 Statistical Parameters of Fibre Reinforced Polymeric Materials

The flexural behavior of FRP bridge decks is influenced by not only sectionproperties such as the moment of inertia and section modulus, but also materialproperties. FRP decks are formed with orthotropic material of which importantproperty is the modulus of elasticity, tensile strength, and

Poisson ratio inboth parallel and perpendicular axes to fibres; the values and ranges of the engineering and mechanical properties of some common fibres are given in Table 2.4.

Table 2.4: Values and Ranges of the Engineering and Mechanical Properties of Some Common Fibres.

FRP Material / **Property**		**Glass**		**Aramid**		**Carbon**		
		E-Glass	**S-Glass**	**Kevlar-29**	**Kevlar-49**	**Carbon HM**	**Carbon IM**	**Carbon SM**
Strength	**(Mpa)**	3400	4445	2800-3600	2900-3600	2700	2910	3530
Young's Modulus	**(Gpa)**	73-81.4	87-89	69-83	125	758-903	380-647	230
Density	**Gr/cm^3**	2.56-2.62	2.5-2.54	1.44	1.44	1.76-2.13	1.76-2	1.76
Ultimate Strain	**%**	4.4-4.88	4.9-5.7	3.6-4.4	2.2-2.8	0.27-0.3	0.4-0.5	1.4-1.5

Source: (Bashar 2012)

2.12 Structural Safety

Risk could generally be defined as a combination of probability and negativeconsequence coupled with an event during a defined time period. It is difficult to define safety but it could be said that safety refers to the lowprobability of failure in a structure or a structural member at a certain limit state.The safety of a structure is traditionally verified by two parameters, a resistanceparameter, *R*, and a load effect parameter, *S*. *R* and *S* originate from the French words*résistance* and *solicitation*. The basic structural design criterion is generally written as:

$R - S \geq 0$ (2.7)

Similar methods are used both in the ultimate limit state as well as in the serviceabilitylimit state, i.e. when considering deflections for example. The problem gets probabilistic whensome or all of the variables are stochastic. Now, the question has advanced from adeterministic answer, *yes* or *no*, to a more describing answer given by the probability offailure. The basic structural problem can then be rewritten to:

$P_f = P\ (R - S) \leq 0$ (2.8)

Where P_f is the probability of failure.

R and *S* are respectively described by a stochastic variable. Bearing capacity, *R*, isdescribed by $f_R(r)$. Load effect, *S*, is described by $f_S(s)$. Figure 2.1 shows a generalcase where distributions for load carrying capacity and load effect overlap.

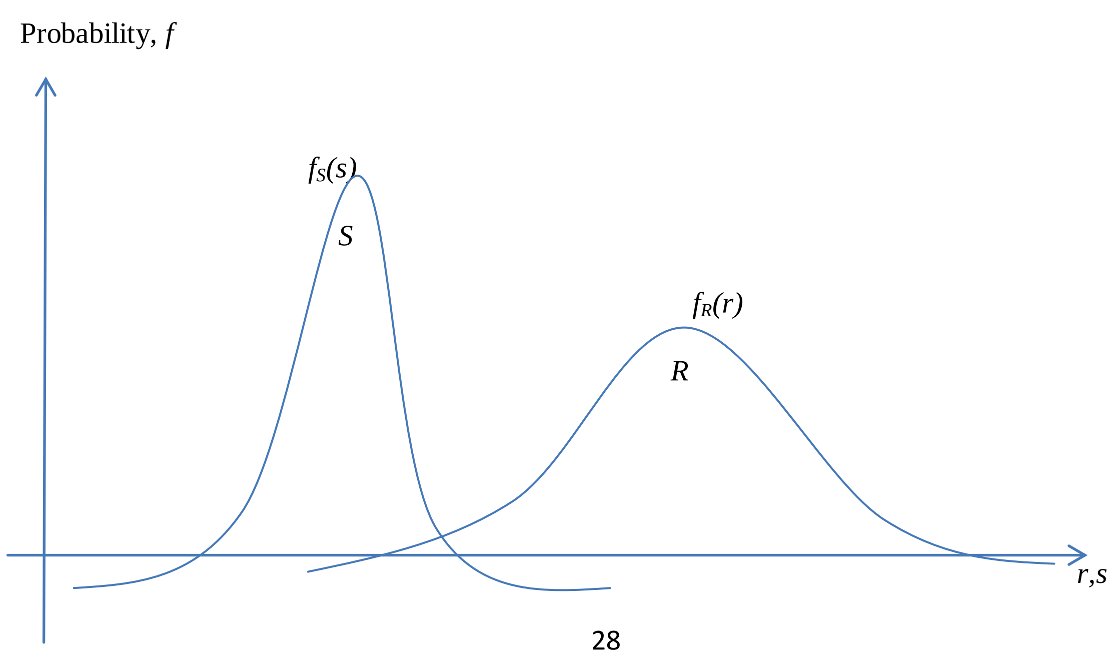


Figure 2.1 Distributions for R and S. (Bergström, 2006)

The structural performance of a whole structure, or a member of it, should generally bedescribed with reference to a specified set of limit states which separate desired states ofthe structure from undesired states. The limit states are divided into the following twocategories (Bergström, 2006):

1.) Serviceability limit states (SLS), which for concrete structures concerns crack widths and deflections.
2.) Ultimate limit states (ULS), which corresponds to the maximum load-carrying capacity or, in some cases, to the maximum applicable strain or deformation.

The effect of exceeding a limit state may be irreversible or reversible. In the irreversible case, the damage or malfunction associated with the limit state being exceeded will remain until the structure has been repaired. In the reversible case, the damage or malfunction will remain only as long as the cause of the limit state being exceeded is present. As soon as this cause ceases to act, a transition from the undesired state back to the desired state occurs (Bergström, 2006).

2.12.1 Safety Class

In this study ACI andEurocodesformulationsfor the loading system on the CFRP deck is considered. However the Swedishdesign code, *“Boverketskonstruktionsregler(1994)”*, suggests that the choice of safety class should regardwhat the extent of human injuries would be in the event of the failure of a building orbuilding element; this is also considered alongside the ACI and Eurocodes of practice. Consequently, *Safety class 1* is used for cases where there is no risk of severe injury.*Safety class 2* is used when there is some risk of severe human injury and *Safety class 3*when the risk for human injury is large. Each safety class is assigned a probability offailure, according to Table 2.5.

Table 2.5Safety class, Safety Indices, and Probability of Failure.

SAFETY CLASS	1	2	3
Probability of Failure, Pf	10^{-4}	10^{-5}	10^{-6}
Safety Index, β	3.72	4.26	4.75

(Source: Boverkets, 1994)

Safety index, β, which is related to either serviceability or ultimate limit states, shouldbe calculated on yearly-basis. Theoretically, this means that, in safety class 3 with$P_f=10^{-6}$, one out of one million identical structures will reach failure in current limitstates. The actual probability of failure is in practice often higher than what thecalculation gives (Abejide, 1997).

When considering a probability of 10^{-6} in philosophic terms, this is referred to as *deminimis*. (Bergström, 2006) This means in reality, that the risk cannot be sensed and thereforeneglected.

2.12.2 Partial coefficients

Today's design codes are built-up using partial coefficients on loads and materialproperties. For example, in Equation (2.9)

$$f_d = \frac{f_k}{\gamma_m} . \frac{\mathrm{K}}{\eta} \tag{2.9}$$

The characteristic stress capacity, f_k, is reducedthrough γ_m and γ_n to the design value, f_d. Ꝁ considers the load carrying capacity of thematerial and is dependent on the moisture content, duration of the load, etc:η considers the systematic difference between a test specimen and a value in the structure.These coefficients are determined from statistical analysis such that the safety of theentire structure reaches a reliability close to the aimed safety. The β-index, which also isa measurement of the safety, could be determined for the specific structure if thedistribution of all varying parameters is established (Belegundu and Chandrupatla, 1999)

2.13 Probabilistic Design

As described above, the deterministic design criteria in Equation (2.7) describes that theresistance should be greater than the load effect parameter to avoid a failure.The problem becomes probabilistic when statistical distributions of the variables aretaken into account.There are three detail levels when talking about theoretical probabilistic methods. Thefirst method considers the uncertainty with one parameter per *uncertain* variable. Thegenerally accepted *Partial Coefficient Method (PCM) that is used in Euro codes* falls intothis category. The PCM is calibrated against other probabilistic methods and is reallynot a probabilistic method. The next method, called *First Order Reliability Method (FORM)*, considers the uncertainty with two parameters, mean value andvariance, for each uncertain parameter. A measure of the safety is given by the safetyindex, β. The risk of failure could be estimated by:

$$P_f = \phi\,(-\beta) \qquad (2.10)$$

The third and most fundamental theory utilize the exact statistical properties for allvariables. This method gives the most realistic measure of the probability of failure, P_f,and requires often numerical methods to be solved.One method which utilizes the exact statistical properties of all variables is the *MonteCarlo (MC)* method. This is really a simulation method which randomly picks numbersin pair from the *R* and *S* distributions. Each pair of numbers is compared in between. Iffailure occurs, when $R<S$, the result is 1 otherwise 0. Mathematically this will beexpressed by an indicator function, *I( )*, which returns 1 if the failure function is lessthan zero, $G(x) \leq 0$, otherwise it returns 0. This leads to an approximation about thefailure probability, P_f, and variance, given by:

$$\tilde{P}_f = \frac{1}{N}\sum \; I\,(G\,(x) \leq 0 \qquad (2.11)$$

$$\mathrm{Var}\left| \acute{P} \right| = \frac{1}{N} P_f \quad (1 - P_f) \tag{2.12}$$

2.14 The Fundamental Reliability Case of Alumadeck System

The concept of a limit state is often used to help define failures in the context of structural reliability analyses. Limit state can be defined as a formalization of the criteria under which the structure can be considered to have failed Melchers (1987). The basis for this theory is that the variable influencing the strength and loading of the structure can be described by stochastic variables, or by a stochastic process. (Transportation Research Circular, 2005). The variable affecting the strength or resistance is often denoted by *R*, where *R* is a function of several other stochastic variables such as the modulus of elasticity E, area of the cross-section, *A* and bending strength, f_b.

2.15 Reliability Based Design Method

The reliability based design of a standard fibre reinforced deck in recent times is not so common as compared with a conventional concrete deck slab. The basic requirement for design of any structure is the expected loading, the structural strength in terms of stiffness and the method of analysis that will be involved. There are two primary approaches for reliability based deisgn; namely, The Direct Reliability Based Design (DRBD) and The Load and Resistance Factor Design (LRFD) as stated by Ayyub et al, (1998). There are three levels in reliability based designs. These are described in the following paragraphs Ayyub et al, (1998).

Level 1, regards the various variables as single valued and is usually the mean or some characteristic value e.g., the 5% quartile. This is the level used for most design work under the most current codes of practice. The LRFD are called a level 1 reliability method, it utilizes Partial Safety Factors (PSF) that are reliability-based, but the technique does not require the explicit use of probabilistic description of the variables. At this level, it is not possible to make statements about the probability of failure of a structure. The direct reliability-based design approach can include both Level 2 and Level 3 reliability methods; and are based on the moments (mean and variance) of random variables and sometimes with a linear approximation of non-linear limit states.

Level 2 defines Stochastic variables which are represented by two properties; the mean and the variance and where necessary sometimes the Covariance. This method provides an approximation of the probability of failure.

Level 3 on the other hand, uses complete probabilistic characteristics of the random variable. For this level, it is assumed; information that fully describes the entire distributions for all the different stochastic variables are involved in the analysis. Given that these assumptions are correct, it is possible to make statements regarding the precise value for the probability of failure. Therefore, Level 3 reliability analysis will not be employed in this research work due to the fact that it is somewhat impossible to make assumptions that are exactly as correct, real accurate and precise in any given model.

2.16 Finite-Element Method

This approach discretizes the structure into small divisions (elements) where each element is defined by a specified number of nodes. The behaviour of each element (and ultimately the structure) is assumed to be a function of its nodal quantities (displacements and/or stresses), that serve as the primary unknowns in this formulation. This is one of the most general and accurate methods to use, because it does not put any limitation on the geometry, loads, or boundary conditions, and can be applied to open/closed girders and static/dynamic analysis. Additionally, the structure's response can always be improved by refining the mesh and increasing the number of nodes (or degrees of freedom) for each element. However, the rather involved modeling and analysis efforts required by this method may in some cases make it impractical for preliminary analysis (Benedittiand Tralli, 1989).

2.17 Stochastic Finite Element Method

Stochastic finite element method has recently become an active area of research. As the name suggests, researchers in this field attempt to combine two crucial methodologies developed to deal with the complex problems of modern engineering. The finite element analysis and the stochastic(probabilistic) analysis. The stochastic analysis refers to the explicit treatment of uncertainties in any quantity entering the corresponding deterministic analysis at a specific period of time. The exact values of these quantities are usually unknown because they cannot be precisely measured (Klieber and Hein, 1992). It is used to describe the merging of advanced reliability methods with the finite element method to obtain probability estimates for predefined performance criteria. These methods are generally applicable to both linear and non-linear problems. Stochastic finite element method is the generalization of the deterministic finite element method to incorporate the random fluctuations in material and geometric properties of the model and the random forces that may act on it (Shekar et al, 2007).The aim of stochastic finite element is two folds; first, to compute the variability of the response of a random system and subsequently, using these results to estimate the structural reliability (Shekar et al, 2007). The key steps involved in the analysis of the system using stochastic finite element method are:

(i) Selection of appropriate probability models to describe the uncertainties in the system parameters and the boundary conditions.

(ii) Discretization of the random fields, i.e., the replacement of these random fields by an equivalent set of random variables.

(iii) Formulation of finite element equations, using standard methods like energy method, virtual work method or weighted residual method and its solution.

(iv) Estimation of system response statistic, which involves the inversion of random matrix operators.

(v) Using these results to make a safety assessment of the structure.

Stochastic Finite Element Method (SFEM), combines areas of finite element analysis and that of reliability. The distinguishing feature of stochastic finite element method, which is based on the perturbation approach, is treating probabilistic non-linear problem with deterministic computational techniques of the mathematical properties of linear operators (Raji, 2003). SFEM is an extension of the classical deterministic FE approach to the stochastic framework i.e. to the solution of stochastic (static and dynamic) problems involving finite elements whose properties are random. From a mathematical point of view, SFEM can be seen as a powerful tool for the solution of stochastic partial differential equations (PDEs) and it is treated as such in numerous studies where convergence and error estimation issues are examined in detail (Stefanou, 2008).

In order to apply the finite element technique, the region of interest is descritised by a finite element mesh. The basic idea of the mean-based, second-moment analysis as used in stochastic finite element analysis is to expand, via Taylor series, all the vector and the matrix stochastic field variables typical of deterministic finite element method about the mean values of the random variables, to retain only up to second order method terms and to use in the analysis only the first tier statistical moments. In this way, equations for the expectation and cross-covariance of the nodal displacement can be obtained in terms of the nodal displacement derivatives with respect to the random variables (Kleiber and Hein, 1992; Raji, 2003; Musa, 2003; Stefanou, 2008).

CHAPTER THREE

METHODOLOGY

3.1 General

The methodology adopted is in conformity withthe safety of the structural members in construction and in service to sustain the expected design loads needed to be resisted by the resisting moment of the slab deck.If due consideration is not given to the design methodology, the expected service design requirements will not be met, and this will consequently lead to failure of the structural member.

In most cases, a line must be drawn between the safety and failure of the structural member. The risk of failure of any structure is often measured in terms of the probability of failure, P_f . Alternatively, the probability of survival is measured in terms of the reliability index, β . Since both quantities are related, it is therefore, imperative that the implied reliability levels of the moment ofresistance of a cellular CFRP decksection be evaluated. Consequently, models for the performance functions for the limit states are developed. The failure mode considered is that due to bending i.e. deformation caused by flexure due to maximum moment. The safety margin is obtained by equating the resistance of the deck and the load effects computed by simple structural analysis. The basic variables were identified, while their statistical behaviouris obtained from literature. Offshore deck platformis considered and dead load, live loads in submerged and un-submerged marine environmentare the two load categories considered in this work.

The probability of failure for a newly constructed structural member, designed in safetyclass 3 according to the Swedish codes (Boverket, 2004), should by definition be equal or less than onein a million on a yearly basis. The other way around says that, only one out of one million structural members should fail every year. The safety of the member mayhowever change during the lifetime as degradation might occur. For example,corrosion of steel reinforcement will affect the safety and behavior of the structurenegatively, as well as a decreased effective height caused by removal or damage of concrete during loading. If these mechanisms are taken into consideration the safety could sooner or later become deficient. In contrast to this, strengthening of thestructure will increase the safety.

3.2 First Order Reliability Method (FORM)

This section presents a basic introduction to the FORM concept. Considering Figure 3.1, the probability that a load effect, *S*, falls into an infinitesimalinterval *ds* at *s* which is $f_S(s).ds$. Also, the probability that *R* falls in or under this interval is $\int_{-\infty}^{s} f_R\ (r)\ dr$.The probability that *S* falls in this interval *ds* when $R \leq S$will result to$f_S(s).ds\ .\ \int_{-\infty}^{s} f_R\ (r)\ dr$

The expression gives the probability that $R \leq S$ is:

$$P_f = P\ (R - S) \leq 0 = \int_{-\infty}^{\infty} f_s\ (s)\ .\ [\int_{-\infty}^{s} f_R\ (r)\ .\ dr]\ \mathrm{ds} = \int_{-\infty}^{\infty} f_s\ (s) f_R(\mathrm{r})\ ds \qquad (3.1)$$

This could be viewed upon as the volume of the two dimensional joint densityfunctions from the failure surface, and can be seen in Figure 3.1. *R* and *S* are plotted asprobability functions on the *r* and *s* axes. The limit state equation, $G=R\text{-}S=0$, separatesthe safe from the unsafe region, dividing the volume into two parts. The volume of thepart cut away and defined by $s > r$ corresponds to the probability of failure. The designpoint $(r^*; s^*)$ is located on this straight line where the joint probability density isgreatest. If failure is to occur it is likely to be there.The desired safe state is above the failure surface, defined as $R\text{-}S=0$, and undesiredfailure state is below.

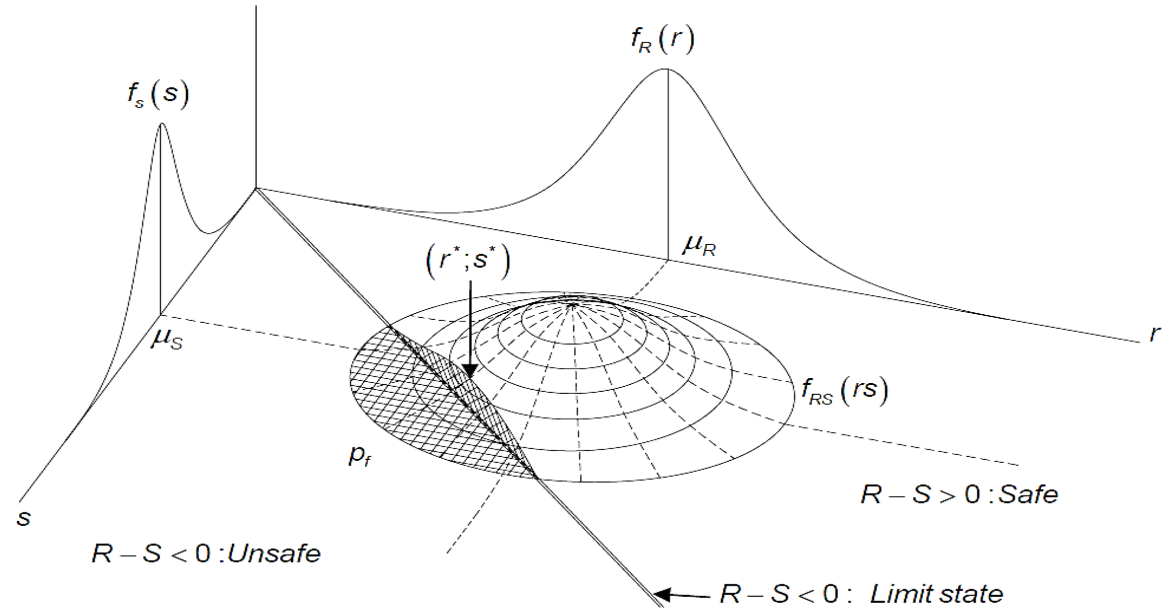


Figure 3.1: 3-D View of Two Random Joint Density Functionsf_{RS}(rs), (Bergström, 2006)

If *R* and *S* are normally distributed and statistically uncorrelated, then:

$R \in N\,(M_R, \sigma_R)$

$S \in N\,(M_S, \sigma_S)$

The safety margin, M is defined as:

$$M = R - S \tag{3.2}$$

Then it is also valid that:

$M \in N\,(M_M, \sigma_M)$

Where $M_M = M_R - M_S$ and

$$\sigma_m = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{3.3}$$

The distribution of *M* is schematically given in Figure 3-2. Failure occurs when M < 0.

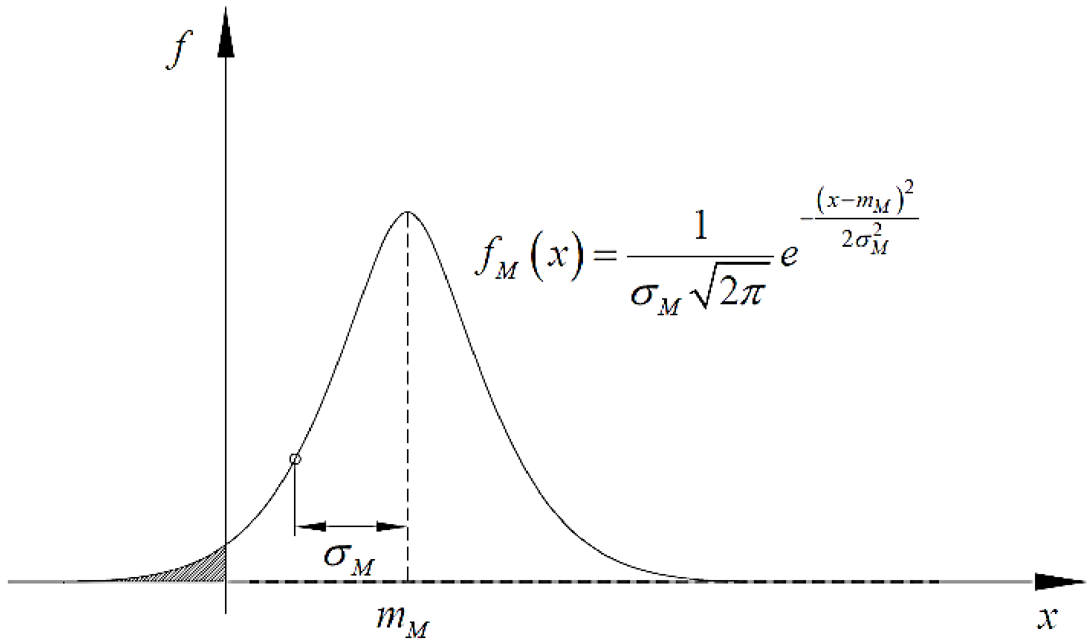


Figure 3.2 Distribution for the Variable M. Failure occurs when M < 0. (Bergström, 2006)

$$P_f = P\ (M<0) = \int_{-\infty}^{0} f_M\,(x)dx = \frac{1}{\sigma_{M\sqrt{2\pi}}}\int_{-\infty}^{0} e^{\frac{x-m_M}{2\sigma_M^2}}\,dx \tag{3.4}$$

Now let,

$$\frac{x-m_M}{\sigma_M} = y\ \rightarrow\ \frac{1}{\sigma_M}\ dx = dy \tag{3.5}$$

$$P_f = P\ (M<0) = \frac{1}{\sqrt{2\pi}}\int e^{\frac{y^2}{2}}\,dy = \ \phi\left(-\frac{m_M}{\sigma_M}\right) = \ \phi(-\beta) \tag{3.6}$$

ϕ (·) is the standardized normal distribution function. This function, given in Figure 3-3, has mean value 0 and standard deviation 1. If R and S are normally distributed, the safety index, β, is calculated as:

$$\beta = \frac{m_M}{\sigma_M} = \frac{m_R - m_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{3.7}$$

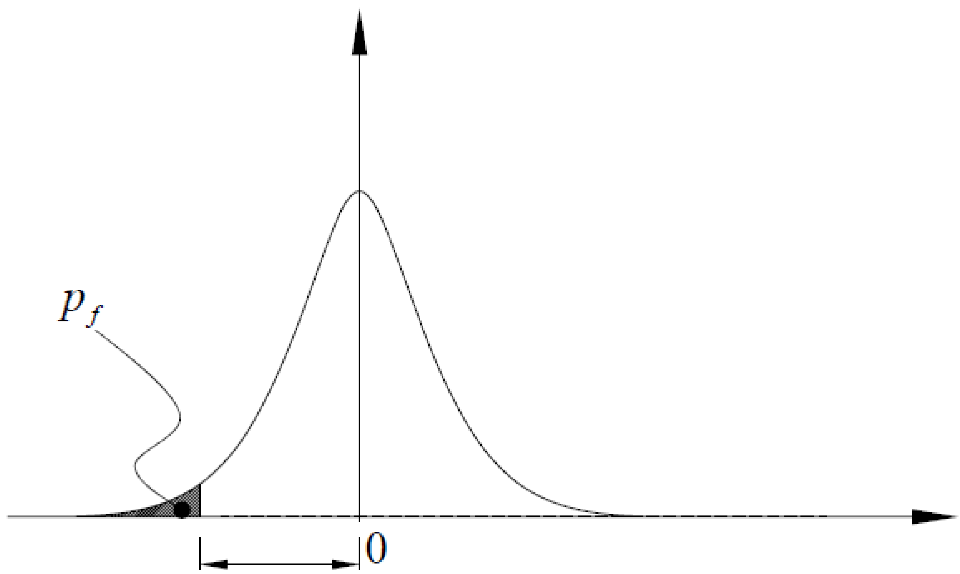
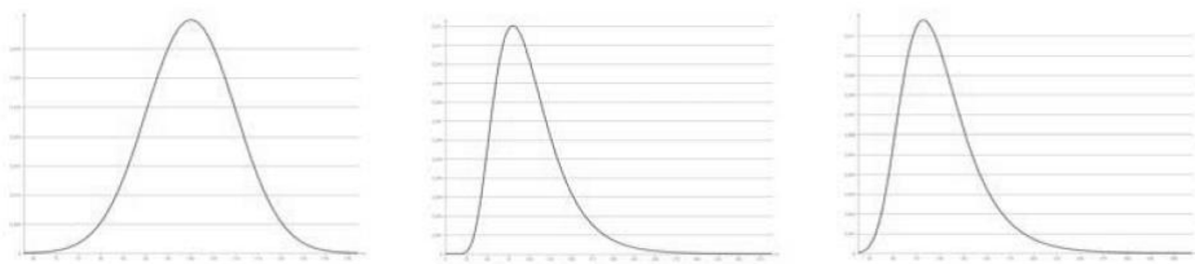


Figure 3.3 The Standardized Normal Distribution Function Safety Index β, is connected to a Certain Probability of Failure, $P_{f\beta}$(Bergström, 2006)

3.3 Parameters of the CFRP Deck

Focus is generally put on distributions for material properties and geometries on thereal structure, as these parameters tend to be assumed as the crucial ones. Parameters are important when designing or retrofitting, especially for oldmaterialsin which properties are hard to translate to modern materials. Old steel inbridges built from 1800 to 1960 could, for instance, show a large variance, (Lawson,1989). One should however not forget to analyze the load situation. If the loaddistribution is poorly established the probabilistic model will give unreliable answers.There is a variety of distributions that could be chosen to describe a certain parameter (Bergström, 2006). Take for instance the log-normal distribution. It may be suitable if the values from thestudied quantity are not allowed to be less than zero, although the mean value is closeto zero. One example of this is the tensile strength of concrete. Geometrical variablesand modulus of elasticity is normally well described by the common normaldistribution. When considering the maximum value for wind load or snow load onannual basis, it is shown that the *Gumbel*distribution, a type-I distribution, may besuitable (Thoft-Christensen & Baker, 1982). Figure 3.4 shows general examples ofnormal, Gumbel and log-normal distributions. (Bergström, 2006



Arbitrary Normal Dist. Arbitrary Log-Normal Dist. Arbitrary GumbelDist

Figure3.4 Probability Distributions. (Bergström, 2006)

3.4 General Description

The deck section proposed is of CFRP material, having a thickness of 100mm, a breath span of 1850mm and length 10m, simply supported on a 300mm x 300mm aluminium girder of equivalent length of slab 10m via shear connectors using aluminium angles welded on the aluminium girder and embedded into the concrete. The proposed section is assumed symmetrical about a horizontal plane; it will accommodate both positive and negative bending moments this is as shown in Fig 3.5 below; finite element analysis is considered.

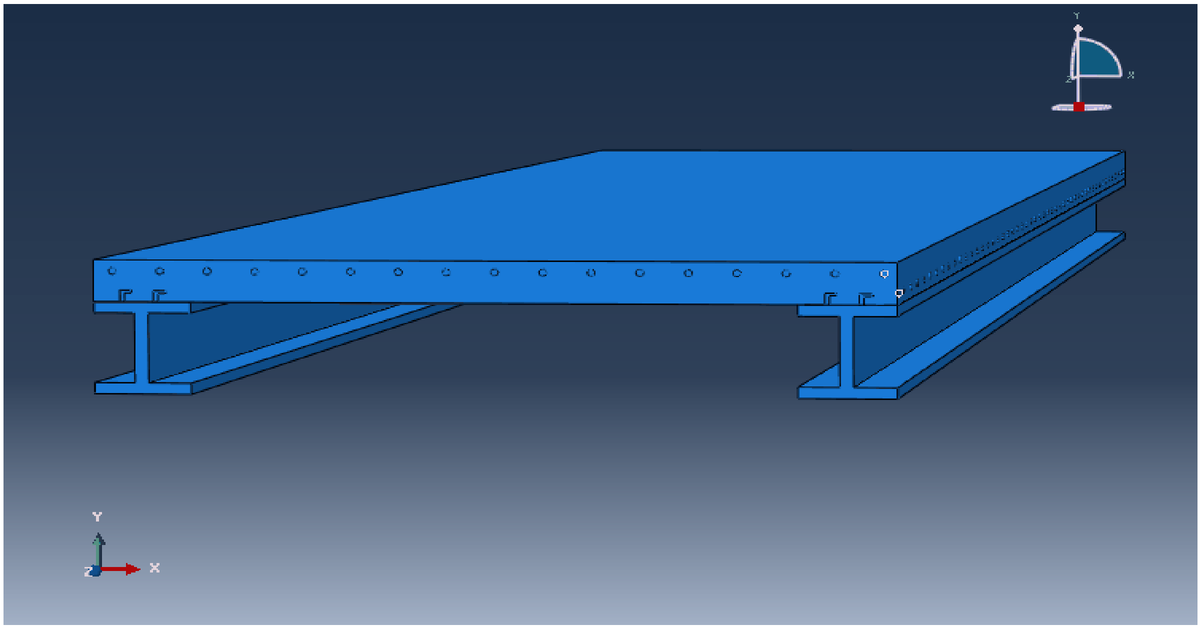


Fig 3.5 Proposed Deck on Aluminium Girder Model: (SimuliaAbaqus, 6.10)

The strength limit state is considered for the design, with loads being represented by applied moments and the resistance by the moment carrying capacity. The mode of failure considered in this work would be governed by AASHTO LRFD (2010) standard of design for the FRP deck section, although safety checks will be made on the girder section as well as using a specified aluminum alloy girder section. The reliability analysis is performed using First Order Reliability Method as proposed by Gollwitzer, et al, (1988).

3.5 Performance Model of FRP Deck

The deck prototype is modeled for performance in service loads. The deck is of CFRP material; made by using high strength cement concrete and prestressed FRP tendons. Since its thickness will be efficient in carrying higher compressive loads; it is also an efficient means of increasing strength and stiffness of the section. The deck in question is subjected to static live loads as well as varying live loads depending on the weight of water pressure.

A standard assembly of the load considered was a simply supported deck on aluminium girders. An arching capacity was considered and analysed on the deck to account for the improved load carrying capacity of the deck section. This is based on kinematics and the non-linear stress-strain properties of the concrete (Rankine and Long, 1997).

3.5.1 Load Analysis

The fibre reinforced deck is analysed in the form of a simply supported spanning deck on aluminum girders. The loading on the deck is a combined load of; Cargo weight, Unit weight of the reinforced plastic deck, Live loads on the deck resulting from Green Sea, human activities, equipment weight on deck, and in submerged cases water head, for the purpose of this thesis an assumed loading of 15kN/m^2 was used, the detail view of loading are as given in Figure 3.6. A clearer version of Figure 3.6 is given in Appendix VI.

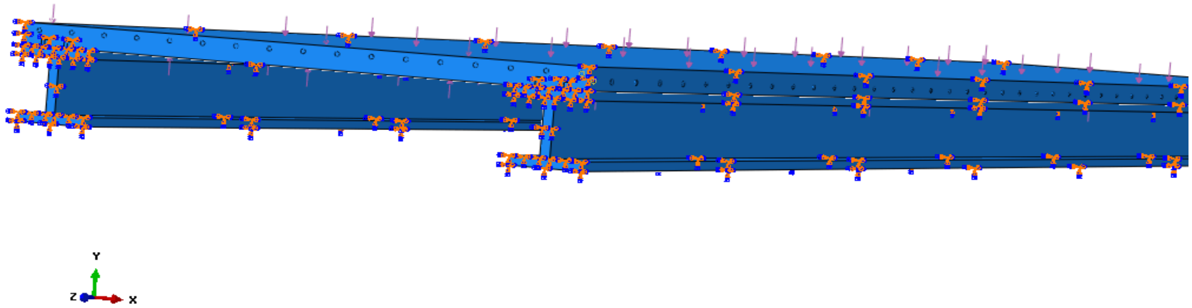


Fig 3.6: Loading on Aluminium Girder Model: (SimuliaAbaqus, 6.10)

Although the loads on the deck will vary depending on the service use, the deck can be sectioned and designed for harbour platform, vessel offices, vessel storage room, vessel living spaces, and naval usage considering the imposed loads from air-craft, fighter jets, helicopters, stealth jets and drones. The specified unit weight of every particular property is derived and the deck is designed based on the ultimate load of the intended use of the area either as office, storage and harbor platform to accommodate the maximum weight of a container or containers, or open deck for accommodating specified number of jets as design requirement will consider. The restraint/boundary condition of the model is as given in Figure 3.7. A clearer version of Figure 3.7 is given in Appendix VI.

The detailed boundary conditions as well as the total number of nodes are shown in Appendix II.

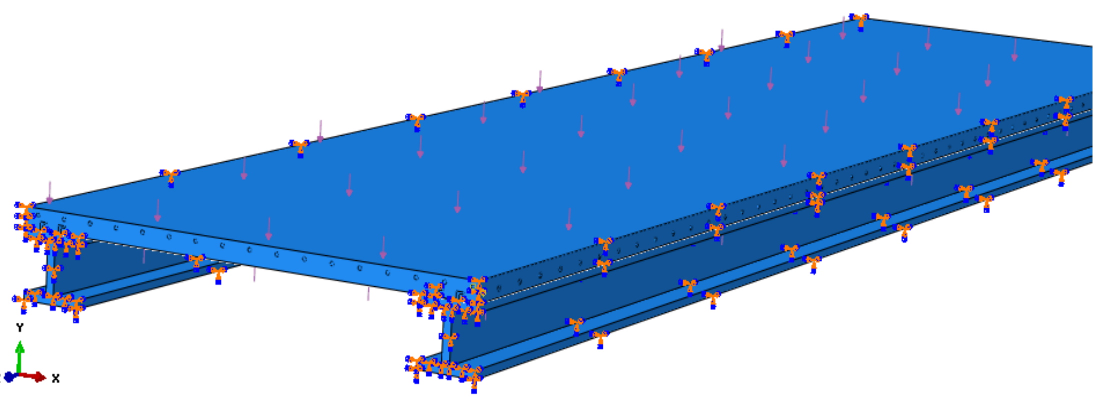


Fig 3.7: Boundary conditions on Deck and Aluminium Girder Model: (SimuliaAbaqus, 6.10)

3.6 Performance Functions for Reliability Analysis

Table 3.1 gives the essential design parameters for the stochastic analysis used in the probabilistic determination of the safety criterion of the CFRP deck:

Table 3.1: Parameters of Stochastic Model

S/N	Basic Variable	Mean	Std Dev.	Cov	Probability Distribution

1	Compressive strength of concrete, f_{cu}	30N/mm^2	4.5N/mm^2	0.150	Lognormal
2	Tensile strength of CFRP, f_{frp}	2250N/mm^2	67.5N/mm^2	0.030	Weibull
3	Area of CFRP, A_{frp}	50.265mm^2	0.75mm^2	0.015	Normal
4	Breadth, b	1000mm	50mm	0.050	Normal
5	Effective depth, d	150mm	68.46mm	0.456	Normal
6	Live load, Q_k	2.25N/mm^2	0.645mm	0.287	Gumbel
7	Length, L	1850mm	75mm	0.240	Normal
8	Elastic modulus of CFRP, E_{frp}	150GPa	4.45N/mm^2	0.030	Weibull
12	Modulus of elasticity of concrete E_c	26 x 10^3 N/mm^2	7.8 x 10^2 N/mm^2	0.030	Lognormal

3.6.1 Bending criterion

An assessment made on a simply supported slab deck and assuming ACI 318, (2002) design code for loading. The ACI code prescribes the highest loading on offshore platforms; considering maximum moments occurring at the mid span is given as:

$$M_a = \frac{wl^2}{8}\ ;\ (S) = \frac{W_u l^2}{8} = (1.4G_k + 1.7Q_k)\frac{l^2}{8} \qquad (3.8)$$

Applied moment (ACI 318)

$$S = (1.4\frac{G_k}{Q_k} + 1.7)\frac{Q_k l^2}{8} \qquad (3.9)$$

Let $\frac{G_k}{Q_k} = \alpha =$ load ratio

$$S = 0.125 Q_k l^2 (1.4\alpha + 1.7) \qquad \text{(ACI 318)} \qquad (3.10)$$

Hence, the moment of resistance, M_R, for the section may be evaluated as:

$$M_r = \left(\phi_C \alpha_1 f_C^{'} ab\right) \times \left(d - \frac{a}{2}\right) \qquad (3.11)$$

Or

$$M_r = \phi_{frp} f_{frp} A_{frp}\left(d - \frac{a}{2}\right) \tag{3.12}$$

Where, $a = \dfrac{\phi_{frp} E_{frp} \varepsilon_{frp} A_{frp}}{\phi_c \left(\alpha_1 f_c^{'}\right) b}$ (3.13)

or,

$$M_r = \phi_{frp} f_{frp} A_{frp}\left(d - \frac{\beta c}{2}\right) \tag{3.14}$$

The limit state function for flexure mode is given as:

$$G(X) = R - S \tag{3.15}$$

Where, $R = M_r$ and $S = M_a$

Therefore, the expression for the performance function for compression failure G(X), in the limit state of bending would be:

$$G(X) = M_r - M_a \quad i = 1, 2\ldots n. \tag{3.16}$$

This, on substitution of values, gives:

$$G(X) = \phi_{frp} f_{frp} A_{frp}\left(d - \frac{a}{2}\right) - 0.125 Q_k L^2 (1.4\alpha + 1.7) \tag{3.17}$$

Equation (3.17) provides the expectation that the resistance moment is greater than the applied moment. Expectation of a variable X, that is, $E(X)$ is the weighted average or mean of all the values that the random variable may take. Consequently, it indicates the value or level of safety attained in the structural member.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Design Data and Specification

The following is the data employed for the practical design process.

Center to Center of Bearing = 1.85m

Live load = 5 kpa (5kN/m^2) from HL – 93 (AASHTO, 2010)

Unit weight of deck = 0.9 kN/m^3

Poisson Ratio, ʋ = 0.34

Density of CFRP = 1.4 g/cm^3

CFRP Strength (f_{frp}) = 3200Mpa

Elastic modulus of CFRP = 200Gpa

Elastic modulus of Aluminum Girder E_{AL}= 69 GPa (69.6 x 10^9 N/mm^2)

4.2 Design Geometry

Height of FRP deck = 100mm

Thickness of wearing surface (assume polymer concrete) = 20mm

Total depth including wearing surface = 120mm

Using the above data and inputing parameters into the FEM design software (SimuliaAbaqus 6.10), the FRP deck is analysed while its failure modes and result output are generated based on the design input. A simple model is created in the ABACUS environment assuming that the aluminium girder is independent of the resulting load conditions since major emphasis is centered on the deck. Secondly, the aluminium girder is made dependent of the load input parameters in order to ascertain the performance of both the deck and girder support under loading conditions. The system of deck panels is assembled by shear connectors at the spaced girder support.

From the Abaqus design environment, the following values were entered and varied within the programme and results were generated. The Table 4.1 – 4.10 below gives the data input, this input is also shown in Appendix II. However, the deformation model of the slab is given as shown in Fig 4.1 – 4.10 from the ABAQUS CAE program.

Table 4.1: Abaqus material properties Input DataModel 1.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	400000Mpa	2750Mpa	0.34	0.019
CONCRETE	2643	31Kpa	30N/mm^2	0.2	0.0035
GIRDER	2700	640000Mpa	400000Mpa	0.33	0.0017

Table 4.2: Abaqus material properties Input DataModel 2.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	350000Mpa	2500Mpa	0.34	0.018
CONCRETE	2643	31Kpa	30N/mm^2	0.2	0.0035
GIRDER	2700	570000Mpa	350000Mpa	0.33	0.0017

Table 4.3: Abaqus material properties Input Data Model 3.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	300000Mpa	2250Mpa	0.34	0.017
CONCRETE	2643	31Kpa	30N/mm^2	0.2	0.0035

GIRDER	2700	500000Mpa	300000Mpa	0.33	0.0015

Table 4.4: Abaqus material properties Input Data Model 4.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	250000Mpa	2000Kpa	0.34	0.013
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	425000Mpa	250000Mpa	0.33	0.0013

Table 4.5: Abaqus material properties Input Data Model 5.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	200000Mpa	1750Mpa	0.34	0.011
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	355000Mpa	200000Mpa	0.33	0.0010

Table 4.6: Abaqus material properties Input Data Model 6.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	150000Mpa	1500Mpa	0.34	0.009
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	287000Mpa	150000Mpa	0.33	0.0006

Table 4.7: Abaqus material properties Input Data Model 7.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	100000Mpa	1250Mpa	0.34	0.007
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	138000Mpa	100000Mpa	0.33	0.0004

Table 4.8: Abaqus material properties Input Data Model 8.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	50000Mpa	1000Mpa	0.34	0.005
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035

GIRDER	2700	69000Mpa	50000Mpa	0.33	0.0002

Table 4.9: Abaqus material properties Input Data Model 9.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	25000Mpa	500Mpa	0.34	0.002
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	6900Mpa	5000Mpa	0.33	0.0002

Table 4.10: Abaqus material properties Input Data Model 10.

Material	Density	Youngs Modulus	Yield Stress	Poisson Ratio	Strain
CFRP	1400	2500Mpa	250Mpa	0.34	0.001
CONCRETE	2643	31Kpa	$30N/mm^2$	0.2	0.0035
GIRDER	2700	3000Mpa	2500Mpa	0.33	0.0002

However, the deformation model of the deck slab using finite element analysis generated from Abaqus CAE is as shown below: The finite element analysis, carried out in Chapter 3, for the slab deck model yielded results indicating that the material properties of the deck is sufficient to provide adequate resistance against deformation and differential settlement, the result of the Finite Element Analysis is as shown in Appendix I and III. The stress patterns and deformations are discussed further.

4.2.1 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.1. A clearer version of Figure 4.1 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.1. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

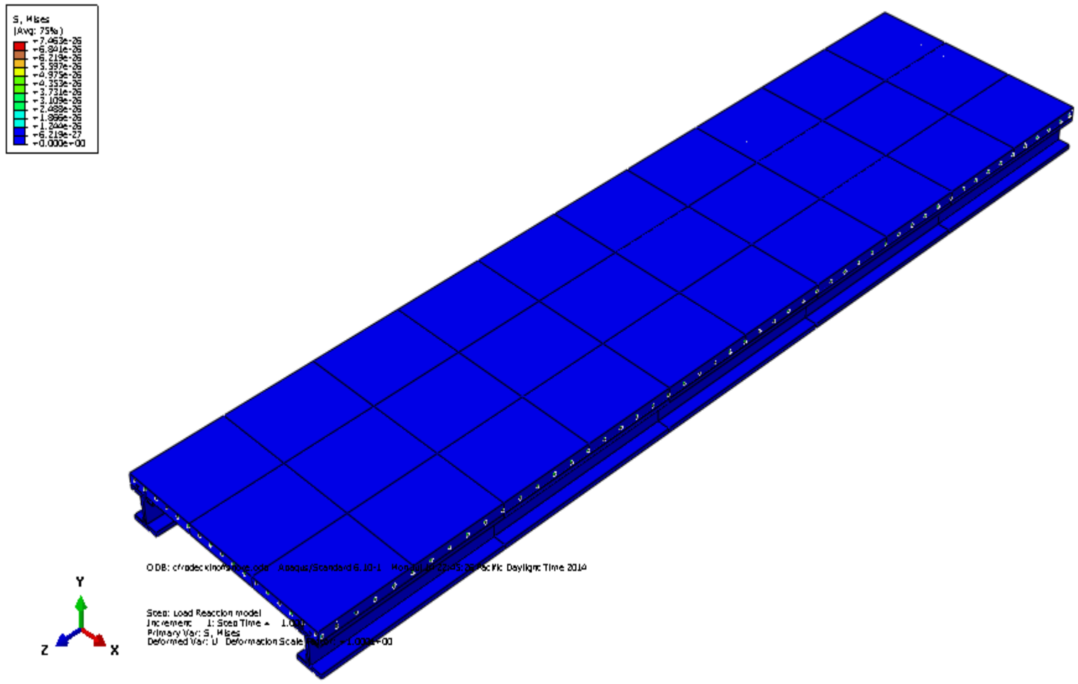


Fig 4.1: Abaqus Deformation Model 1

4.2.2 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.2. A clearer version of Figure 4.2 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.2. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

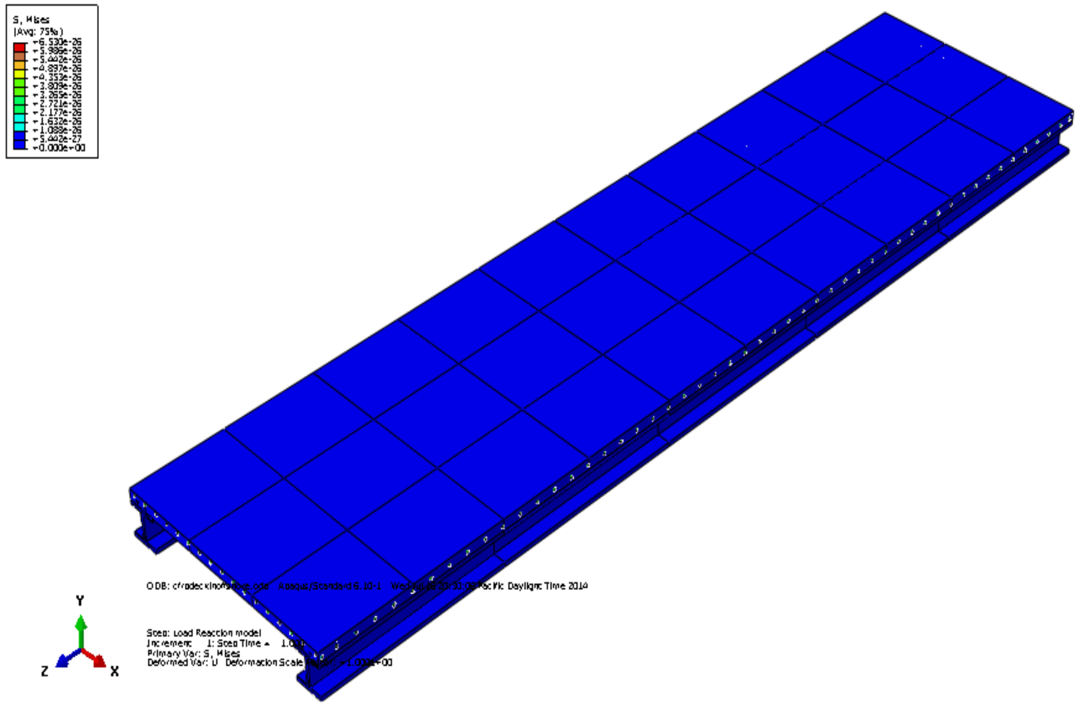


Fig 4.2: Abaqus Deformation Model 2

4.2.3 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.3. A clearer version of Figure 4.3 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.3. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

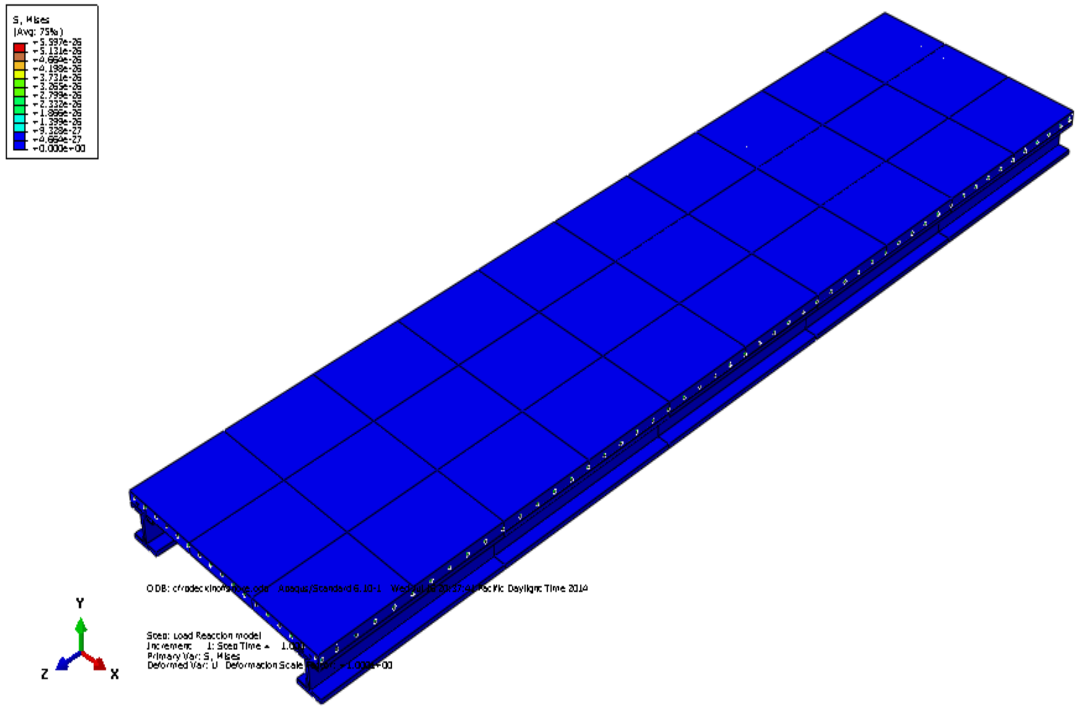


Fig 4.3: Abaqus Deformation Model 3

4.2.4 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.4. A clearer version of Figure 4.4 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.4. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

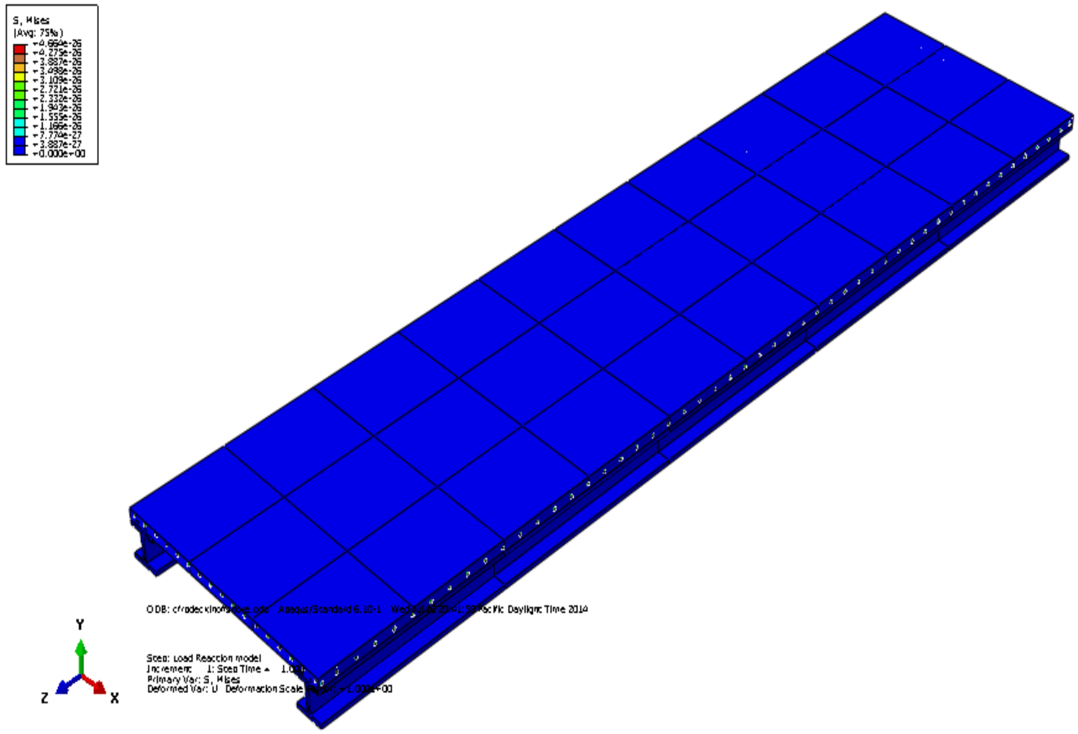


Fig 4.4: Abaqus Deformation Model 4

4.2.5 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.5. A clearer version of Figure 4.5 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.5. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

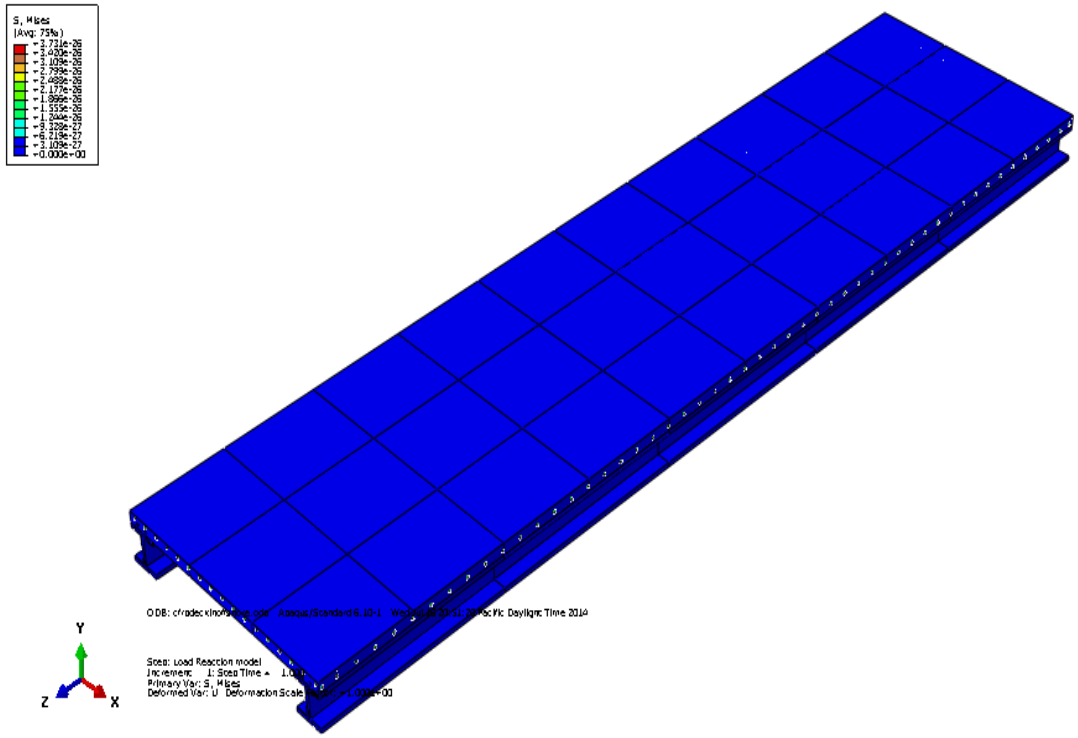


Fig 4.5: Abaqus Deformation Model 5

4.2.6 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.6. A clearer version of Figure 4.6 can be seen in Appendix VI.The analysis shows that there are no Von Mises stresses within the deck based on Table 4.6. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

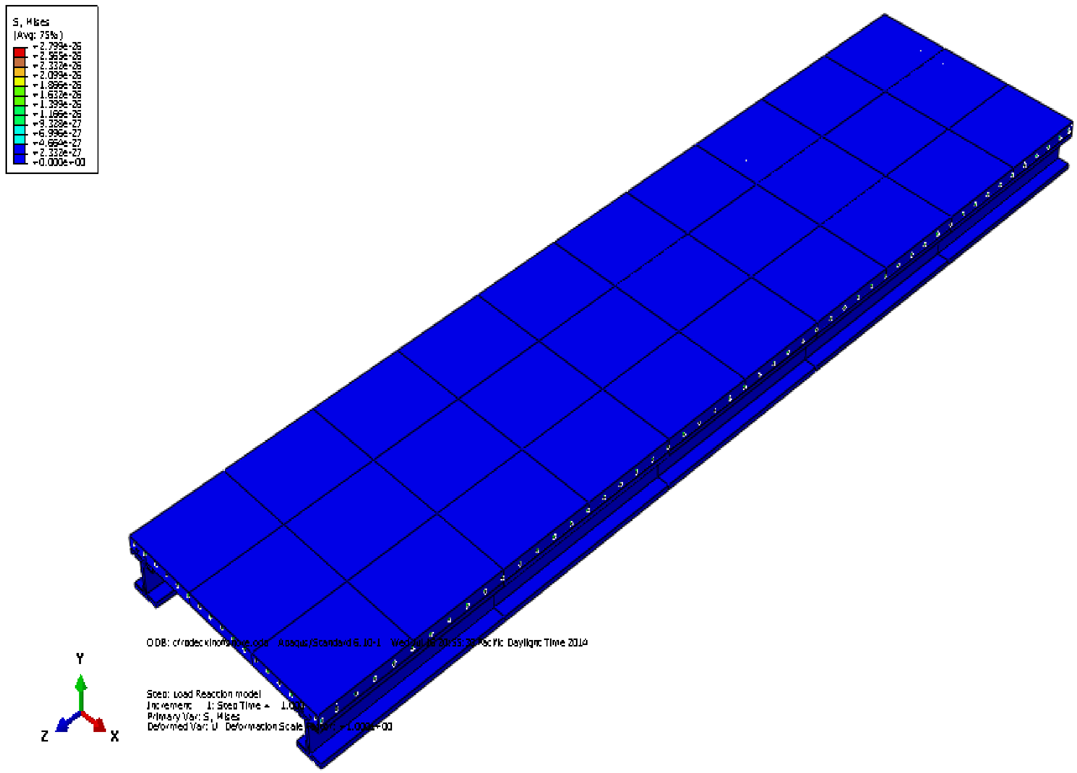


Fig 4.6: Abaqus Deformation Model 6

4.2.7 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.7. A clearer version of Figure 4.7 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.7. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

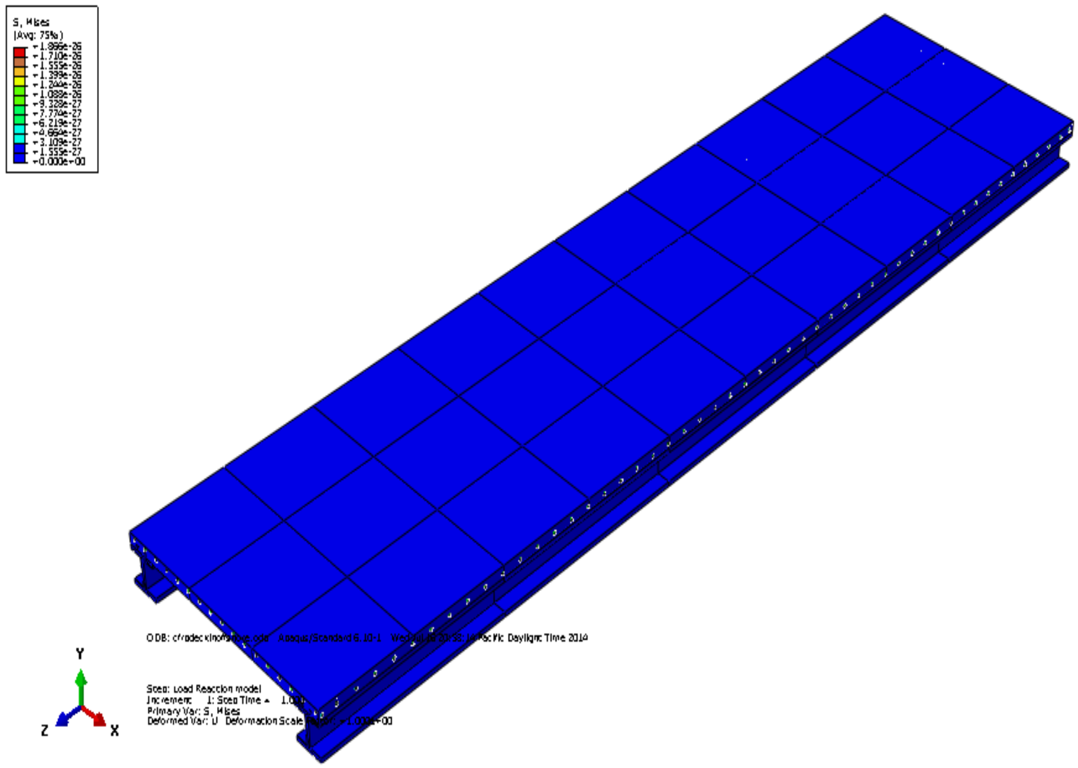


Fig 4.7: Abaqus Deformation Model 7

4.2.8 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.8. A clearer version of Figure 4.8 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.8. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

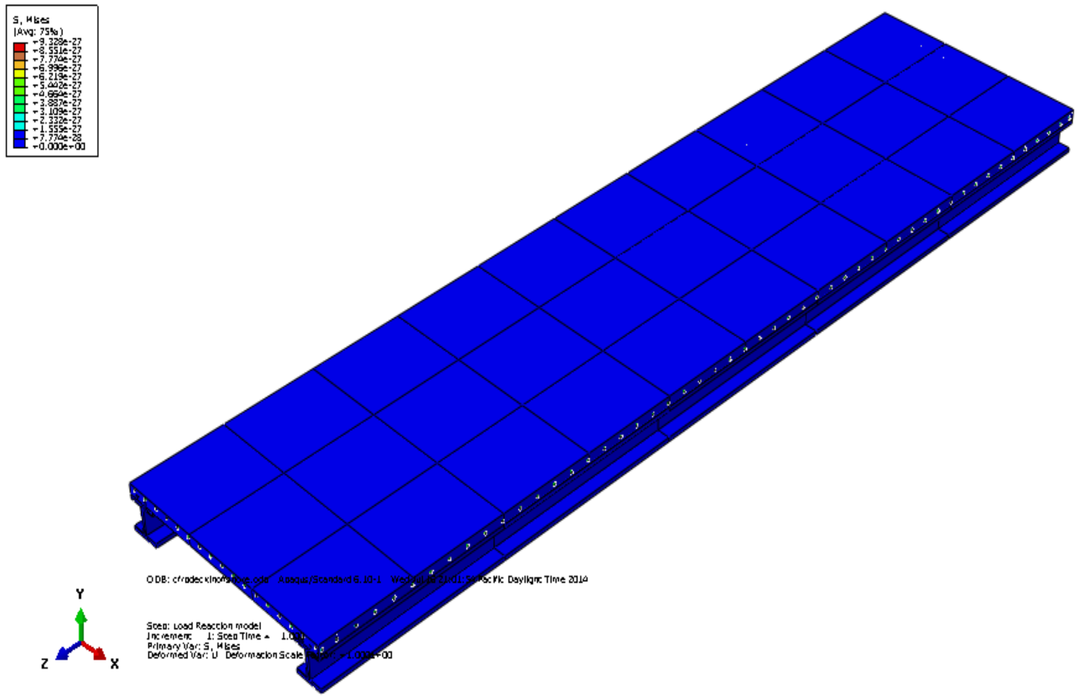


Fig 4.8: Abaqus Deformation Model 8

4.2.9 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.9. A clearer version of Figure 4.9 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.9. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads.

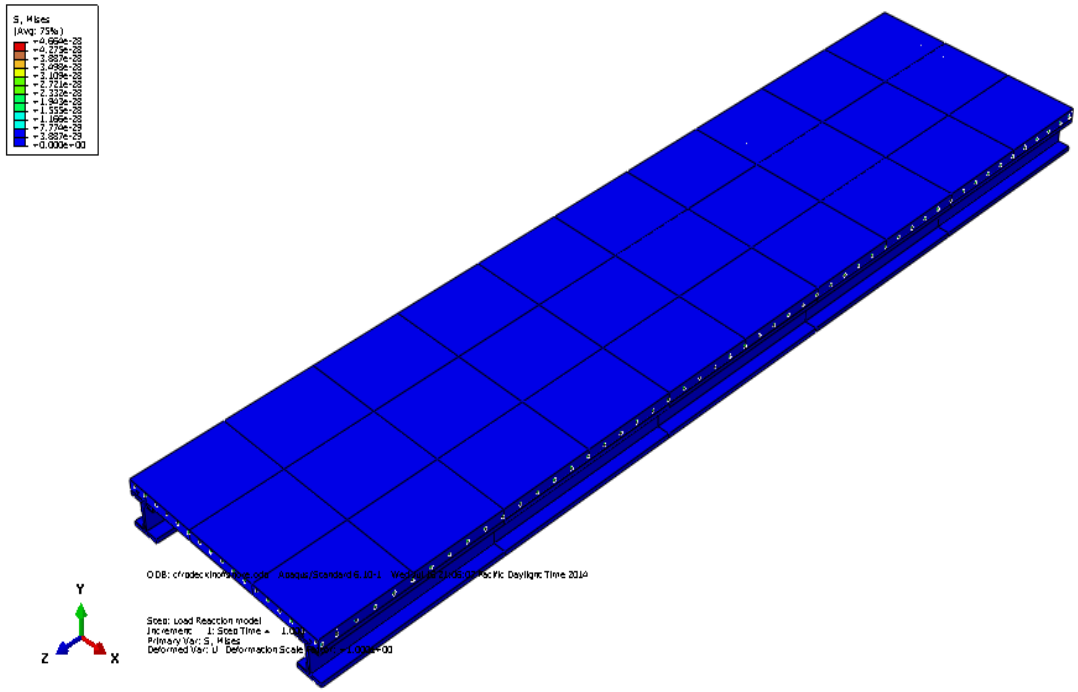


Fig 4.9: Abaqus Deformation Model 9

4.2.10 Stress Pattern in the Slab Deck

The Von Mises stress pattern obtained after the analysis for the deck reinforced with CFRP can be seen in the deformed diagram of the model shown in Figure 4.10. A clearer version of Figure 4.10 can be seen in Appendix VI. The analysis shows that there are no Von Mises stresses within the deck based on Table 4.10. The contour blue indicates zero Von Mises stresses and hence it is an indication that the slab deck is stable after the deformation caused by the applied loads, although, there were no values for the stress deformation, this therefore indicates that the material properties of the deck is not adequate to safely sustain the loads on the deck, this results to failure of the deck.

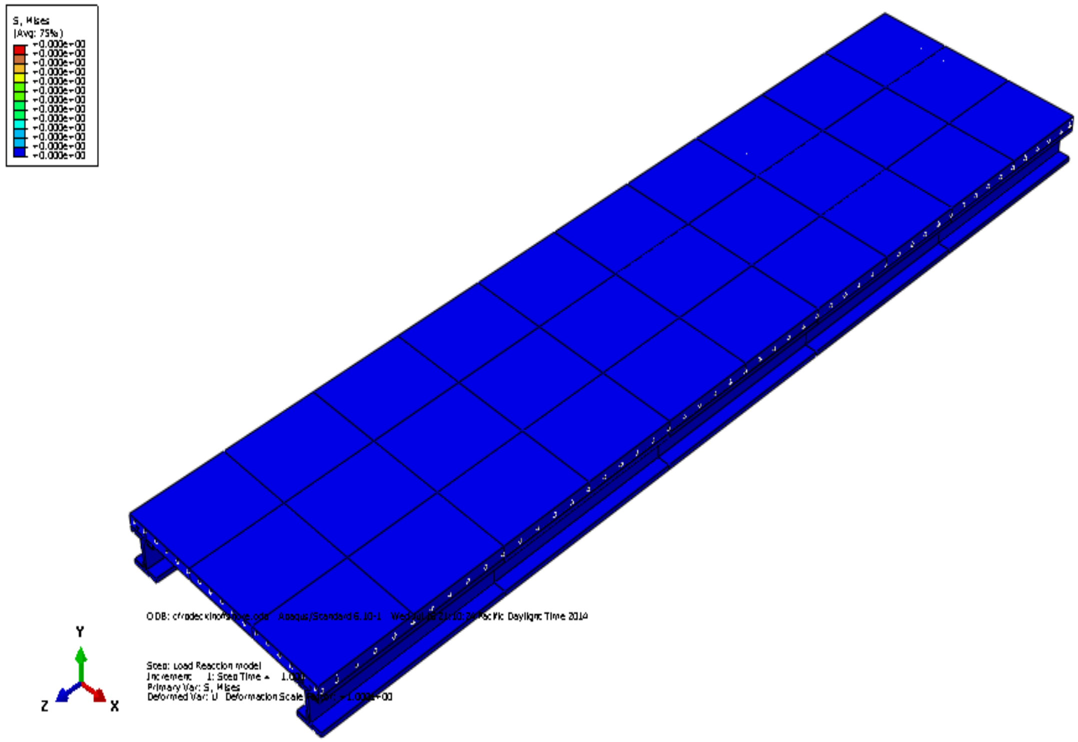


Fig 4.10: Abaqus Deformation Model 10

4.3Design Parameters using First Order Reliability Method

Using the FORM software (Gollwitzer, et al, 1988) to ascertain the safety indices for the CFRP deck, the results generated are as illustrated in Appendix V; according to the strength of fibre while fixing the span and concrete strength as constants; the result of the graph is illustrated in Figs 4.11 – 4.16.

The values of safety indices plotted against load ratiosareas presented.

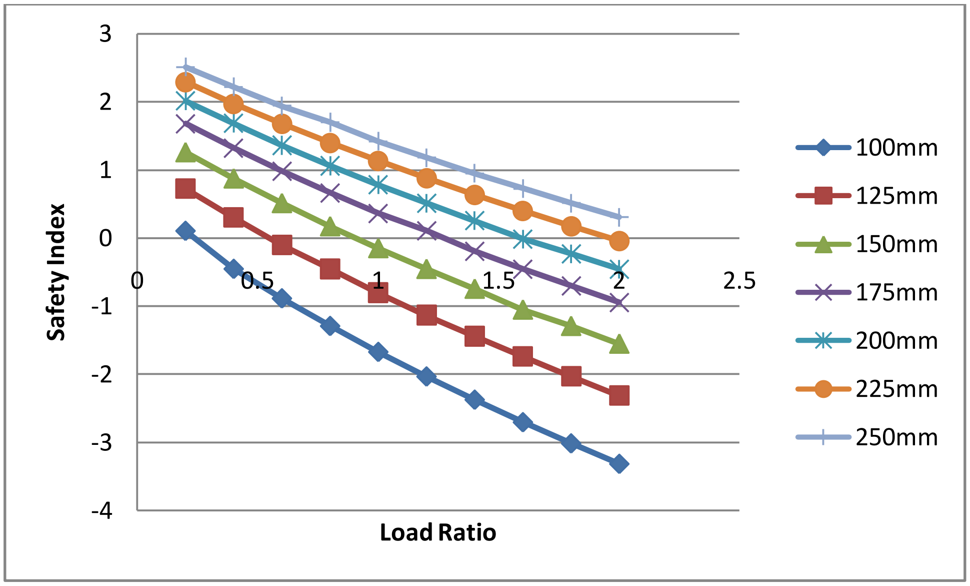


Fig 4.11: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu} = 1500N/mm^2, f_{ck} = 30N/mm^2, d : 100mm - 250mm)

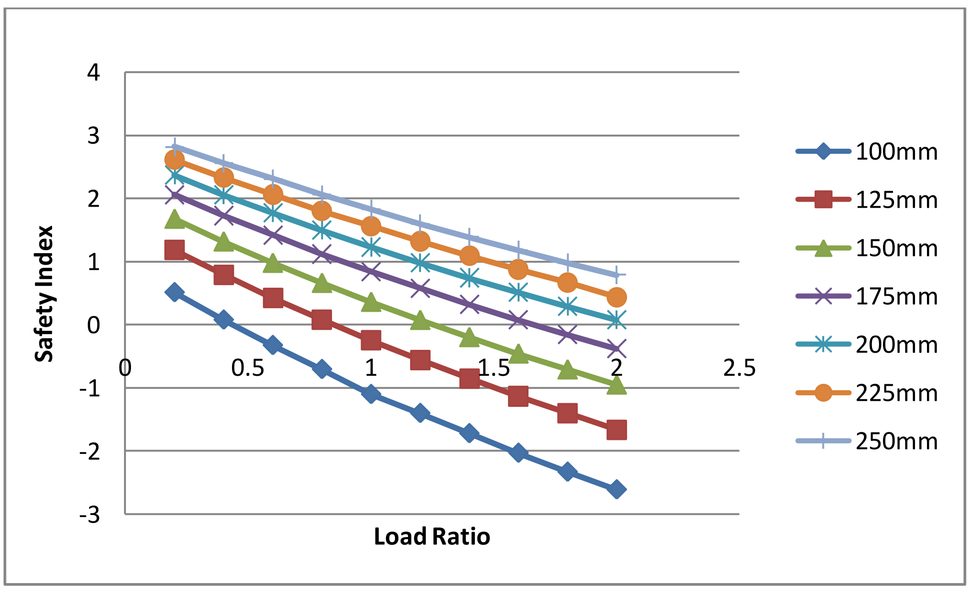


Fig 4.12: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu}= 1750N/mm^2, f_{ck} = 30N/mm^2, d: 100mm - 250mm)

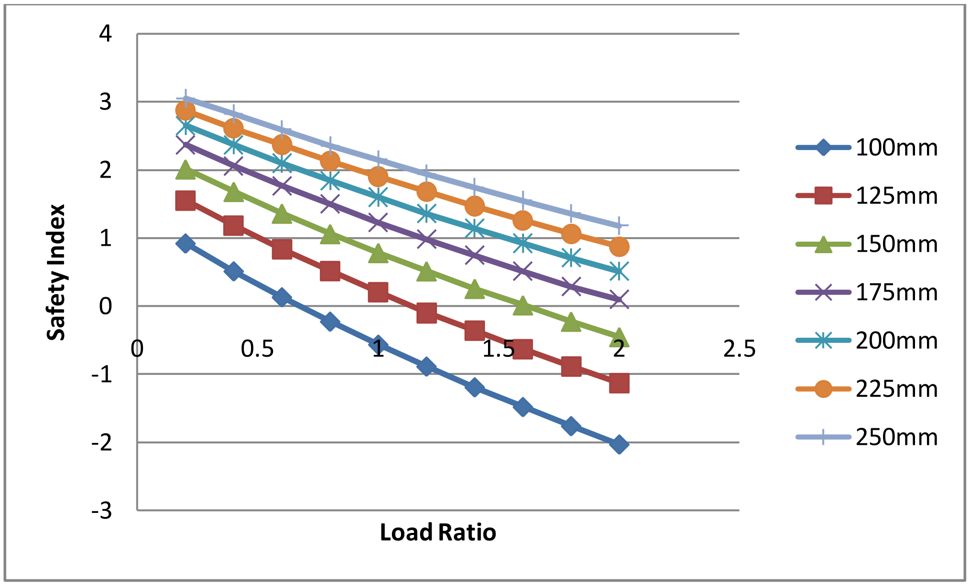


Fig 4.13: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu} = 2000N/mm^2, f_{ck} = 30N/mm^2, d : 100mm - 250mm)

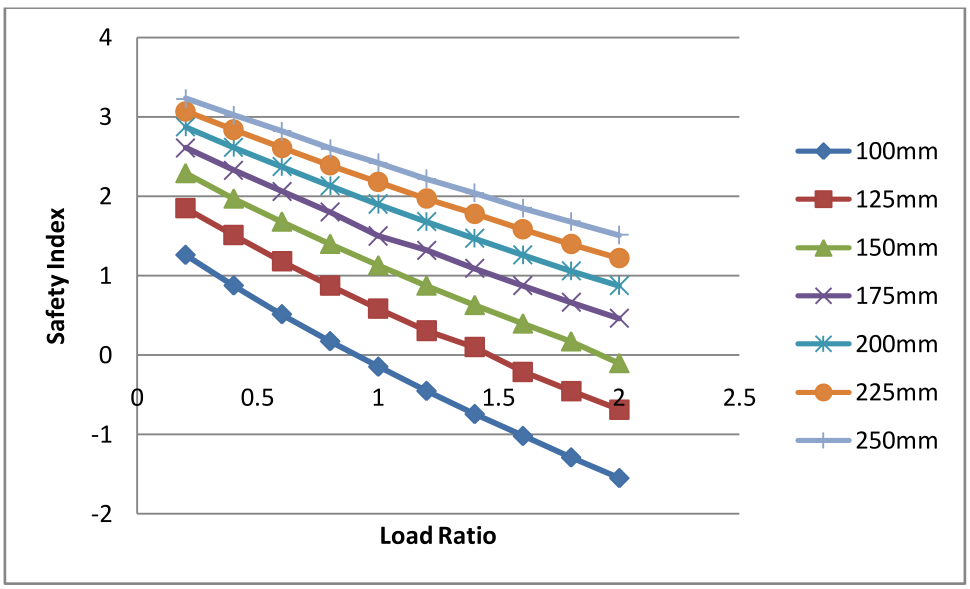


Fig 4.14: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu} = 2250N/mm^2, f_{ck} = 30N/mm^2, d : 100mm - 250mm)

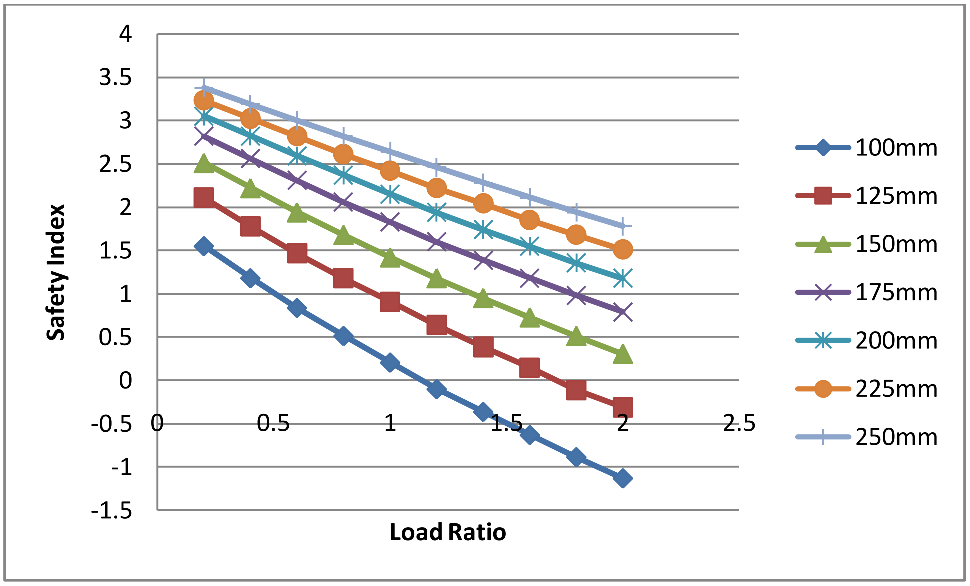


Fig 4.15: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu} = 2500N/mm^2, f_{ck} = 30N/mm^2, d : 100mm - 250mm)

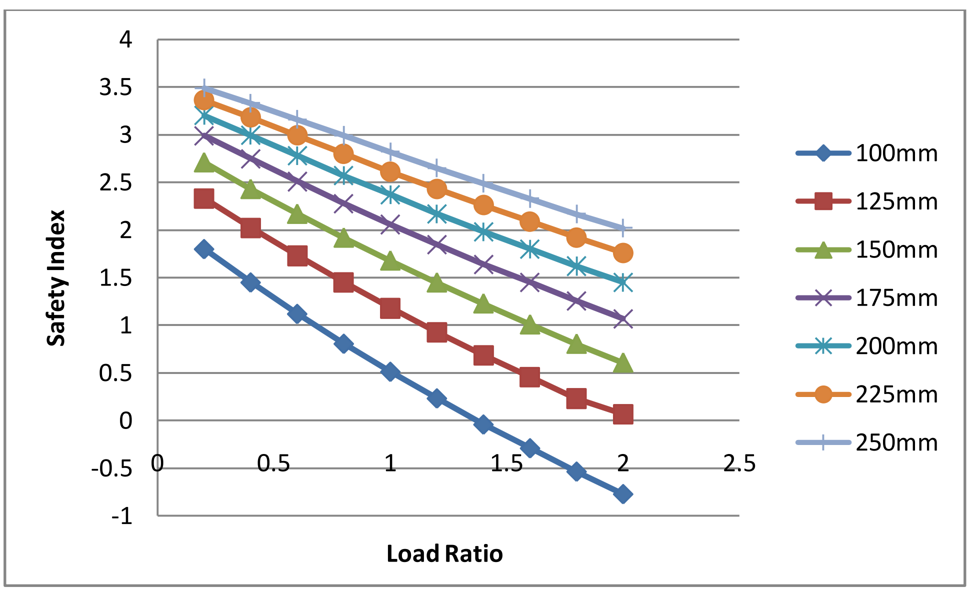


Fig 4.16: Variation of safety index against Load Ratios;

(L = 1850mm, f_{fpu} = 2750N/mm^2, f_{ck} = 30N/mm^2, d : 100mm - 250mm)

4.4 Discussion of Results

The results generated as shown in Figs 4.11 to 4.16 indicates that the lower the effective depth and increasing load ratios the more susceptible the failure of the deck, consequently with lower FRP tensile strength, the lower the safety level. However, increase in effective depth as well as increase in CFRP strength increases safety index greatly and the slab is more stable and can also withstand increasing load ratio up to a value of 1.2 at a tensile strength of 2750N/mm^{2}and depth of 100mm before failure. Thus, the safety margin of the modeled slab deck is adequate. The result of the FORM analysis is as shown in AppendixV.The stochastic evaluation of the performance of Carbon Fibre Offshore Plastics (CFRP) offshore platform considering submerged and partially submerged environmental conditions using Swedish codeBoverket (2004)as indicated in Figs 3.6 to 3.7 showed that the deck can adequately transmit the given loading conditions when designed in accordance with Boverket (2004). Also, the results of the Finite Element analysis carried out on the deck shown in Figs 4.1 to 4.10 showed that the resisting moment of the CFRP deck was adequate. The flexural as well as shearing resistance as shown in Fig 4.1 is found within safety limit; about 500% greater than that of a steel reinforced concrete platform.

However considering the serviceability limit state of deflection, the CFRP platforms did not show noticeable deformation in the geometry of the deck from the finite element analysis. From Table 4.16, the imposed load that can be sustained on a 150mm thick CFRP deck is 20kN/m^2; while that of 200mm thick CFRP deck is 30kN/m^2

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the input design data as outlined in section 4.1,

1. That the assembled section of the slab deck, the carbon fibre reinforcement as well as the aluminium girder did not suffer deformation due to the material properties provided; due to an increase in overall member stiffness of the entire section which is efficient to sustain the ultimate loads during the service life time.
2. The finite element analysis was carried out and deformations were obtained, the von mises stress distribution indicates that, the performance of the slab is efficient up to a minimum of 500Mpa and fails from values below 500Mpa. The performance of the slab at varying loads shows that the slab can sustain imposed loads when submerged or partially submerged in marine environments.
3. The analysis generated by the FORM shows that, with lower load ratios and increasing effective depth the slab performance criteria is adequate resulting to a positive safety index value of **(β = 3.49)**. But as the load ratio increases with decrease in tensile strength as well as stiffness of the deck, the safety index is low and the slab fails with a minimum value of **(β = -3.31)**.
4. The theoretical framework for risk assessment based on the Joint Council for Structural Safety JCSS (2003) illustrates that the output of a quantitative risk analysis is generally a quantitative measure of consequences and associated probabilities, (Inger et al, 2008). Thus the design of an element based on

uncertainties such as Quantitative Risk Analysis (QRA) and Structural Reliability Analysis (SRA) indicates that; the reliability index of epistemic uncertainties for structural safety should be taken as ($\beta = 3$) corresponding to a failure probability of 10^{-3} (Faber et al, 2008). From the design model of the deck using FORM, the maximum safety index was given as ($\beta = 3.49$) which is higher than the limit set by the JCSS (2003) code, hence the deck is adequately reliable to a probability of $> 10^{-3}$; and conforms to the standard specified by the JCSS code.

5.2 Recommendations

1. From the load resistance point of view, CFRP deck is a reliable alternative to common steel and reinforced concrete decks for offshore platforms and bridge construction, irrespective of increasing high loads, cargo loads as well as varied harzardous environmental conditions and varied load ratios, the material property of CFRP makes it efficient during the service life of the deck.
2. There is need for proper effective design of structures subjected to marine environments.
3. The design load of offshore platforms should not be greater than 20kN
4. The thickness of the deck should not be less than 100mm, so as to provide enough concrete cover to the reinforcing tendons from chloride attacks.
5. The maximum thickness of the deck to resist flexure is 250mm, failure due to shear should be carried when this thickness is exceeded.
6. However, further research can be made on the behavioural performance of the model in increasing temperature conditions as well as the limiting fire resistance duration of CFRP decks.

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APPENDIX I: FINITE ELEMENT ANALYSIS OF CFRP PLATFORMS ON ALUMINIUM GIRDER IN OFFSHORE

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PROCESSING PART, INSTANCE, AND ASSEMBLY INFORMATION

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END PROCESSING PART, INSTANCE, AND ASSEMBLY INFORMATION

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E L E M E N T   Q U A L I T Y C H E C K S

***NOTES: DISTORTED ISOPARAMETRIC ELEMENTS: ANGLE BETWEEN ISOPARAMETRIC LINES

IS LESS THAN 45 DEGREES OR GREATER THAN 135 DEGREES.

TETRAHEDRAL QUALITY MEASURE: VOLUME OF TETRAHEDRON DIVIDED BY THE

VOLUME OF EQUILATERAL TETRAHEDRON WITH SAME CIRCUMSPHERE RADIUS;

0 FOR DEGENERATE TETRAHEDRON AND 1 FOR EQUILATERIAL TETRAHEDRON. IT

IS RECOMMENDED THAT THE TETRAHEDRAL QUALITY MEASURE BE GREATER THAN

0.02, THE MIN INTERIOR (DIHEDRAL) ANGLE BE GREATER THAN 10 DEGREES,

AND THE MAX INTERIOR (DIHEDRAL) ANGLE BE LESS THAN 160 DEGREES.

TRIANGULAR QUALITY MEASURE: AREA OF TRIANGLE DIVIDED BY THE AREA OF

EQUILATERAL TRIANGLE WITH SAME CIRCUMCIRCLE RADIUS; 0 FOR DEGENERATE

TRIANGLE AND 1 FOR EQUILATERAL TRIANGLE. IT IS RECOMMENDED THAT THE

TRIANGULAR QUALITY MEASURE BE GREATER THAN 0.01, THE MIN INTERIOR

ANGLE BE GREATER THAN 10 DEGREES, AND THE MAX INTERIOR ANGLE BE LESS

THAN 160 DEGREES.

NODAL ADJUSTMENTS ARISING FROM CONTACT INTERACTIONS AND/OR TIE

CONSTRAINTS CAN CAUSE SEVERE ELEMENT DISTORTION. IT MAY BE NECESSARY

TO REMESH IN ORDER TO REDUCE THE AMOUNT OF ADJUSTMENT.

***WARNING: 60 elements are distorted. Either the isoparametric angles are out

of the suggested limits or the triangular or tetrahedral quality

measure is bad. The elements have been identified in element set WarnElemDistorted.

***WARNING: The aspect ratio for 80 elements exceeds 100 to 1. The elements

have been identified in element set WarnElemAspectRatio.

Distorted isoparametric elements

Element	Min/max angle	Adjusted nodes
GIRDER-2.8	9.32876	NO
GIRDER-2.11	11.8491	NO
GIRDER-2.12	20.8295	NO
GIRDER-2.14	34.8595	NO
GIRDER-2.17	25.0713	NO
GIRDER-2.18	39.9616	NO
GIRDER-2.28	9.32876	NO
GIRDER-2.31	11.8491	NO
GIRDER-2.32	20.8295	NO
GIRDER-2.34	34.8595	NO

GIRDER-2.37	25.0713	NO
GIRDER-2.38	39.9616	NO
GIRDER-2.48	9.32876	NO
GIRDER-2.51	11.8491	NO
GIRDER-2.52	20.8295	NO
GIRDER-2.54	34.8595	NO
GIRDER-2.57	25.0713	NO
GIRDER-2.58	39.9616	NO
GIRDER-2.68	9.32876	NO
GIRDER-2.71	11.8491	NO
GIRDER-2.72	20.8295	NO
GIRDER-2.74	34.8595	NO
GIRDER-2.77	25.0713	NO
GIRDER-2.78	39.9616	NO
GIRDER-2.88	9.32876	NO
GIRDER-2.91	11.8491	NO
GIRDER-2.92	20.8295	NO
GIRDER-2.94	34.8595	NO
GIRDER-2.97	25.0713	NO
GIRDER-2.98	39.9616	NO
GIRDER-3.8	9.32876	NO
GIRDER-3.11	11.8491	NO
GIRDER-3.12	20.8295	NO
GIRDER-3.14	34.8595	NO
GIRDER-3.17	25.0713	NO
GIRDER-3.18	39.9616	NO
GIRDER-3.28	9.32876	NO
GIRDER-3.31	11.8491	NO

GIRDER-3.32	20.8295	NO
GIRDER-3.34	34.8595	NO
GIRDER-3.37	25.0713	NO
GIRDER-3.38	39.9616	NO
GIRDER-3.48	9.32876	NO
GIRDER-3.51	11.8491	NO
GIRDER-3.52	20.8295	NO
GIRDER-3.54	34.8595	NO
GIRDER-3.57	25.0713	NO
GIRDER-3.58	39.9616	NO
GIRDER-3.68	9.32876	NO
GIRDER-3.71	11.8491	NO
GIRDER-3.72	20.8295	NO
GIRDER-3.74	34.8595	NO
GIRDER-3.77	25.0713	NO
GIRDER-3.78	39.9616	NO
GIRDER-3.88	9.32876	NO
GIRDER-3.91	11.8491	NO
GIRDER-3.92	20.8295	NO
GIRDER-3.94	34.8595	NO
GIRDER-3.97	25.0713	NO
GIRDER-3.98	39.9616	NO

Elements with large aspect ratio

Element Adjusted nodes

------------------ --------------

GIRDER-2.3	NO
GIRDER-2.4	NO
GIRDER-2.5	NO
GIRDER-2.6	NO
GIRDER-2.15	NO
GIRDER-2.16	NO
GIRDER-2.19	NO
GIRDER-2.20	NO
GIRDER-2.23	NO
GIRDER-2.24	NO
GIRDER-2.25	NO
GIRDER-2.26	NO
GIRDER-2.35	NO
GIRDER-2.36	NO
GIRDER-2.39	NO
GIRDER-2.40	NO
GIRDER-2.43	NO
GIRDER-2.44	NO
GIRDER-2.45	NO
GIRDER-2.46	NO
GIRDER-2.55	NO
GIRDER-2.56	NO
GIRDER-2.59	NO
GIRDER-2.60	NO
GIRDER-2.63	NO
GIRDER-2.64	NO
GIRDER-2.65	NO

GIRDER-2.66	NO
GIRDER-2.75	NO
GIRDER-2.76	NO
GIRDER-2.79	NO
GIRDER-2.80	NO
GIRDER-2.83	NO
GIRDER-2.84	NO
GIRDER-2.85	NO
GIRDER-2.86	NO
GIRDER-2.95	NO
GIRDER-2.96	NO
GIRDER-2.99	NO
GIRDER-2.100	NO
GIRDER-3.3	NO
GIRDER-3.4	NO
GIRDER-3.5	NO
GIRDER-3.6	NO
GIRDER-3.15	NO
GIRDER-3.16	NO
GIRDER-3.19	NO
GIRDER-3.20	NO
GIRDER-3.23	NO
GIRDER-3.24	NO
GIRDER-3.25	NO
GIRDER-3.26	NO
GIRDER-3.35	NO
GIRDER-3.36	NO
GIRDER-3.39	NO

GIRDER-3.40	NO
GIRDER-3.43	NO
GIRDER-3.44	NO
GIRDER-3.45	NO
GIRDER-3.46	NO
GIRDER-3.55	NO
GIRDER-3.56	NO
GIRDER-3.59	NO
GIRDER-3.60	NO
GIRDER-3.63	NO
GIRDER-3.64	NO
GIRDER-3.65	NO
GIRDER-3.66	NO
GIRDER-3.75	NO
GIRDER-3.76	NO
GIRDER-3.79	NO
GIRDER-3.80	NO
GIRDER-3.83	NO
GIRDER-3.84	NO
GIRDER-3.85	NO
GIRDER-3.86	NO
GIRDER-3.95	NO
GIRDER-3.96	NO
GIRDER-3.99	NO
GIRDER-3.100	NO

- (RAMP) OR (STEP) - INDICATE USE OF DEFAULT AMPLITUDES ASSOCIATED WITH THE STEP

P R O B L E M   S I Z E

NUMBER OF ELEMENTS IS 1743

NUMBER OF NODES IS 6808

NUMBER OF NODES DEFINED BY THE USER 6808

TOTAL NUMBER OF VARIABLES IN THE MODEL 20424

(DEGREES OF FREEDOM PLUS MAX NO. OF ANY LAGRANGE MULTIPLIER

VARIABLES. INCLUDE *PRINT,SOLVE=YES TO GET THE ACTUAL NUMBER.)

END OF USER INPUT PROCESSING

JOB TIME SUMMARY

USER TIME (SEC) = 0.90000

SYSTEM TIME (SEC) = 0.10000

TOTAL CPU TIME (SEC) = 1.0000

WALLCLOCK TIME (SEC) = 2

1

STEP 1 INCREMENT 1

TIME COMPLETED IN THIS STEP
0.00

S T E P 1 S T A T I C A N A L Y S I S

AUTOMATIC TIME CONTROL WITH -

A SUGGESTED INITIAL TIME INCREMENT OF 1.00

AND A TOTAL TIME PERIOD OF 1.00

THE MINIMUM TIME INCREMENT ALLOWED IS 1.000E-05

THE MAXIMUM TIME INCREMENT ALLOWED IS 1.00

LINEAR EQUATION SOLVER TYPE DIRECT SPARSE

M E M O R Y E S T I M A T E

PROCESS	FLOATING PT OPERATIONS PER ITERATION	MINIMUM MEMORY REQUIRED (MBYTES)	MEMORY TO MINIMIZE I/O (MBYTES)
1	5.68E+006	22	34

NOTE:

(1) SINCE ABAQUS DOES NOT PRE-ALLOCATE MEMORY AND ONLY ALLOCATES MEMORY AS NEEDED DURING THE ANALYSIS,

THE MEMORY REQUIREMENT PRINTED HERE CAN ONLY BE VIEWED AS A GENERAL GUIDELINE BASED ON THE BEST

KNOWLEDGE AVAILABLE AT THE BEGINNING OF A STEP BEFORE THE SOLUTION PROCESS HAS BEGUN.

(2) THE ESTIMATE IS NORMALLY UPDATED AT THE BEGINNING OF EVERY STEP. IT IS THE MAXIMUM VALUE OF THE

ESTIMATE FROM THE CURRENT STEP TO THE LAST STEP OF THE ANALYSIS, WITH UNSYMMETRIC SOLUTION TAKEN

INTO ACCOUNT IF APPLICABLE.

(3) SINCE THE ESTIMATE IS BASED ON THE ACTIVE DEGREES OF FREEDOM IN THE FIRST ITERATION OF THE

CURRENT STEP, THE MEMORY ESTIMATE MIGHT BE SIGNIFICANTLY DIFFERENT THAN ACTUAL USAGE FOR

PROBLEMS WITH SUBSTANTIAL CHANGES IN ACTIVE DEGREES OF FREEDOM BETWEEN STEPS (OR EVEN WITHIN

THE SAME STEP). EXAMPLES ARE: PROBLEMS WITH SIGNIFICANT CONTACT CHANGES, PROBLEMS WITH MODEL

CHANGE, PROBLEMS WITH BOTH STATIC STEP AND STEADY STATE DYNAMIC PROCEDURES WHERE ACOUSTIC

ELEMENTS WILL ONLY BE ACTIVATED IN THE STEADY STATE DYNAMIC STEPS.

(4) FOR MULTI-PROCESS EXECUTION, THE ESTIMATED VALUE OF FLOATING POINT OPERATIONS FOR EACH PROCESS

IS BASED ON AN INITIAL SCHEDULING OF OPERATIONS AND MIGHT NOT REFLECT THE ACTUAL FLOATING

POINT OPERATIONS COMPLETED ON EACH PROCESS. OPERATIONS ARE DYNAMICALY BALANCED DURING EXECUTION,

SO THE ACTUAL BALANCE OF OPERATIONS BETWEEN PROCESSES IS EXPECTED TO BE BETTER THAN THE ESTIMATE

PRINTED HERE.

(5) THE UPPER LIMIT OF MEMORY THAT CAN BE ALLOCATED BY ABAQUS WILL IN GENERAL DEPEND ON THE VALUE OF

THE "MEMORY" PARAMETER AND THE AMOUNT OF PHYSICAL MEMORY AVAILABLE ON THE MACHINE. PLEASE SEE

THE "ABAQUS ANALYSIS USER'S MANUAL" FOR MORE DETAILS. THE ACTUAL USAGE OF MEMORY AND OF DISK

SPACE FOR SCRATCH DATA WILL DEPEND ON THIS UPPER LIMIT AS WELL AS THE MEMORY REQUIRED TO MINIMIZE

I/O. IF THE MEMORY UPPER LIMIT IS GREATER THAN THE MEMORY REQUIRED TO MINIMIZE I/O, THEN THE ACTUAL

MEMORY USAGE WILL BE CLOSE TO THE ESTIMATED "MEMORY TO MINIMIZE I/O" VALUE, AND THE SCRATCH DISK

USAGE WILL BE CLOSE-TO-ZERO; OTHERWISE, THE ACTUAL MEMORY USED WILL BE CLOSE TO THE PREVIOUSLY

MENTIONED MEMORY LIMIT, AND THE SCRATCH DISK USAGE WILL BE ROUGHLY PROPORTIONAL TO THE DIFFERENCE

BETWEEN THE ESTIMATED "MEMORY TO MINIMIZE I/O" AND THE MEMORY UPPER LIMIT. HOWEVER ACCURATE

ESTIMATE OF THE SCRATCH DISK SPACE IS NOT POSSIBLE.

(6) USING "*RESTART, WRITE" CAN GENERATE A LARGE AMOUNT OF DATA WRITTEN IN THE WORK DIRECTORY.

THE ANALYSIS HAS BEEN COMPLETED

ANALYSIS COMPLETE

WITH 2 WARNING MESSAGES ON THE DAT FILE

AND 1 WARNING MESSAGES ON THE MSG FILE

JOB TIME SUMMARY

USER TIME (SEC) = 1.5000

SYSTEM TIME (SEC) = 0.10000

TOTAL CPU TIME (SEC) = 1.6000

WALLCLOCK TIME (SEC) = 4

APPENDIX II: FINITE ELEMENT NODES AND BOUNDARY CONDITIONS OF CFRP PLATFORMS ON ALUMINIUM GIRDER

*Heading

** Job name: cfrpdeckinoffshore Model name: Model-2

```
** Generated by: Abaqus/CAE 6.10-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name="cfrp main"
*Node
      1,  0.400580883, -0.0099831149,           0.
      2,  0.400580883, -0.0099831149,          2.5
      3,  0.795269668, -0.00881043263,           0.
      4,  0.795269668, -0.00881043263,          2.5
      5,    1.1950798, -0.0087058302,           0.
      6,    1.1950798, -0.0087058302,          2.5
      7,   1.59673405, -0.00945165753,           0.
      8,   1.59673405, -0.00945165753,          2.5
      9,   2.00026894, -0.00999638345,           0.
     10,   2.00026894, -0.00999638345,          2.5
     11,    2.3971529, -0.00958610699,           0.
     12,    2.3971529, -0.00958610699,          2.5
     13,   2.80039763, -0.00999208819,           0.
     14,   2.80039763, -0.00999208819,          2.5
     15,   3.19421482, -0.00815661717,           0.
     16,   3.19421482, -0.00815661717,          2.5
     17,   3.59923625, -0.00997079816,           0.
     18,   3.59923625, -0.00997079816,          2.5
     19,   3.99777937, -0.00975033455,           0.
     20,   3.99777937, -0.00975033455,          2.5
     21,   4.39999628, -0.00999999978,           0.
```

```
    22,   4.39999628, -0.00999999978,          2.5
    23,   4.79686069, -0.00949449185,           0.
    24,   4.79686069, -0.00949449185,          2.5
    25,   5.20412683, -0.00910866074,           0.

650,  100,  400,  401,  402, 2805, 2808, 2807, 2806
651, 2810, 2809, 2812, 2811,  403,  101,  405,  404
652, 2814, 2813, 2816, 2815, 2810, 2809, 2812, 2811
653, 2818, 2817, 2820, 2819, 2814, 2813, 2816, 2815
654, 2822, 2821, 2824, 2823, 2818, 2817, 2820, 2819
655, 2826, 2825, 2828, 2827, 2822, 2821, 2824, 2823
656, 2830, 2829, 2832, 2831, 2826, 2825, 2828, 2827
657, 2834, 2833, 2836, 2835, 2830, 2829, 2832, 2831
658, 2838, 2837, 2840, 2839, 2834, 2833, 2836, 2835
659, 2842, 2841, 2844, 2843, 2838, 2837, 2840, 2839
660, 2846, 2845, 2848, 2847, 2842, 2841, 2844, 2843
661, 2850, 2849, 2852, 2851, 2846, 2845, 2848, 2847
662, 2854, 2853, 2856, 2855, 2850, 2849, 2852, 2851
663,  408,  102,  406,  407, 2854, 2853, 2856, 2855
*Nset, nset=_PickedSet2, internal, generate
    1,  2856,     1
*Elset, elset=_PickedSet2, internal, generate
   1,  663,    1
*Nset, nset="main rod", generate
    1,  2856,     1
*Elset, elset="main rod", generate
   1,  663,    1
** Section: reinforcement
```

```
*Solid Section, elset=_PickedSet2, material="cfrp rods"
,
*End Part
**
*Part, name="cfrp rods"
*Node
      1,  0.144791707, -0.00853661261,           0.
      2,  0.144791707, -0.00853661261,          10.
      3,  0.448144197, -0.00982629228,           0.
      4,  0.448144197, -0.00982629228,          10.
      5,  0.743756354, -0.00781131862,           0.
      6,  0.743756354, -0.00781131862,          10.
      7,   1.05457842, -0.00889034383,           0.
      8,   1.05457842, -0.00889034383,          10.
      9,   1.34747052, -0.00967480335,           0.
     10,   1.34747052, -0.00967480335,          10.
     11,   1.64692402, -0.00951515697,           0.
     12,   1.64692402, -0.00951515697,          10.
     13,    1.9503175, -0.00999495666,           0.
     14,    1.9503175, -0.00999495666,          10.
     15,   2.25085354, -0.00996349752,           0.
     16,   2.25085354, -0.00996349752,          10.
     17,    2.4003284, -0.00999461021,           0.
     18,    2.4003284, -0.00999461021,          10.
     19,   2.09391022, -0.00793179683,           0.
     20,   2.09391022, -0.00793179683,          10.
     21,   1.79810858, -0.00981949456,           0.
     22,   1.79810858, -0.00981949456,          10.
```

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    23,   1.50085855, -0.00996307656,           0.
    24,   1.50085855, -0.00996307656,          10.
    25,   1.19269848, -0.0068328483,           0.

3462, 0.00658478308, 0.00752599677,   9.60000038
  3463, -0.00752599677, 0.00658478308,   9.60000038
  3464, -0.00658478308, -0.00752599677,   9.60000038
  3465, 0.00752599677, -0.00658478308,   9.80000019
  3466, 0.00658478308, 0.00752599677,   9.80000019
  3467, -0.00752599677, 0.00658478308,   9.80000019
  3468, -0.00658478308, -0.00752599677,   9.80000019
*Element, type=C3D8R
 1, 137, 140, 139, 138,   1,  37,  36,  35
 2, 141, 144, 143, 142, 137, 140, 139, 138
 3, 145, 148, 147, 146, 141, 144, 143, 142
 4, 149, 152, 151, 150, 145, 148, 147, 146
 5, 153, 156, 155, 154, 149, 152, 151, 150
 6, 157, 160, 159, 158, 153, 156, 155, 154
 7, 161, 164, 163, 162, 157, 160, 159, 158
 8, 165, 168, 167, 166, 161, 164, 163, 162
 9, 169, 172, 171, 170, 165, 168, 167, 166
10, 173, 176, 175, 174, 169, 172, 171, 170
11, 177, 180, 179, 178, 173, 176, 175, 174
12, 181, 184, 183, 182, 177, 180, 179, 178
13, 185, 188, 187, 186, 181, 184, 183, 182
14, 189, 192, 191, 190, 185, 188, 187, 186
15, 193, 196, 195, 194, 189, 192, 191, 190
16, 197, 200, 199, 198, 193, 196, 195, 194
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17, 201, 204, 203, 202, 197, 200, 199, 198

18, 205, 208, 207, 206, 201, 204, 203, 202

19, 209, 212, 211, 210, 205, 208, 207, 206

20, 213, 216, 215, 214, 209, 212, 211, 210

21, 217, 220, 219, 218, 213, 216, 215, 214

22, 221, 224, 223, 222, 217, 220, 219, 218

23, 225, 228, 227, 226, 221, 224, 223, 222

24, 229, 232, 231, 230, 225, 228, 227, 226

25, 233, 236, 235, 234, 229, 232, 231, 230

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830, 3389, 3392, 3391, 3390, 3385, 3388, 3387, 3386

831, 3393, 3396, 3395, 3394, 3389, 3392, 3391, 3390

832, 3397, 3400, 3399, 3398, 3393, 3396, 3395, 3394

833, 3401, 3404, 3403, 3402, 3397, 3400, 3399, 3398

834, 3405, 3408, 3407, 3406, 3401, 3404, 3403, 3402

835, 3409, 3412, 3411, 3410, 3405, 3408, 3407, 3406

836, 3413, 3416, 3415, 3414, 3409, 3412, 3411, 3410

837, 3417, 3420, 3419, 3418, 3413, 3416, 3415, 3414

838, 3421, 3424, 3423, 3422, 3417, 3420, 3419, 3418

839, 3425, 3428, 3427, 3426, 3421, 3424, 3423, 3422

840, 3429, 3432, 3431, 3430, 3425, 3428, 3427, 3426

841, 3433, 3436, 3435, 3434, 3429, 3432, 3431, 3430

842, 3437, 3440, 3439, 3438, 3433, 3436, 3435, 3434

843, 3441, 3444, 3443, 3442, 3437, 3440, 3439, 3438

844, 3445, 3448, 3447, 3446, 3441, 3444, 3443, 3442

845, 3449, 3452, 3451, 3450, 3445, 3448, 3447, 3446

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846, 3453, 3456, 3455, 3454, 3449, 3452, 3451, 3450
847, 3457, 3460, 3459, 3458, 3453, 3456, 3455, 3454
848, 3461, 3464, 3463, 3462, 3457, 3460, 3459, 3458
849, 3465, 3468, 3467, 3466, 3461, 3464, 3463, 3462
850,   34,  134,  135,  136, 3465, 3468, 3467, 3466
*Nset, nset=_PickedSet2, internal, generate
    1,  3468,     1
*Elset, elset=_PickedSet2, internal, generate
   1,  850,    1
*Nset, nset="long side rod", generate
    1,  3468,     1
*Elset, elset="long side rod", generate
   1,  850,    1
** Section: reinforcement
*Solid Section, elset=_PickedSet2, material="cfrp rods"
,
*End Part
**
*Part, name=girder
*End Part
**
*Part, name="slab deck"
*Node
      1,          10.,         1.25,          10.
      2,          10.,   1.14999998,          10.
      3,          10.,         1.25,           9.
      4,          10.,   1.14999998,           9.
      5,          10.,         1.25,           8.
```

6,	10.,	1.14999998,	8.
7,	10.,	1.25,	7.
8,	10.,	1.14999998,	7.
9,	10.,	1.25,	6.
10,	10.,	1.14999998,	6.
11,	10.,	1.25,	5.
12,	10.,	1.14999998,	5.
13,	10.,	1.25,	4.
14,	10.,	1.14999998,	4.
15,	10.,	1.25,	3.
16,	10.,	1.14999998,	3.
17,	10.,	1.25,	2.
18,	10.,	1.14999998,	2.
19,	10.,	1.25,	1.
20,	10.,	1.14999998,	1.
21,	10.,	1.25,	0.
22,	10.,	1.14999998,	0.
23,	9.16666698,	1.25,	10.
24,	9.16666698,	1.14999998,	10.
25,	9.16666698,	1.25,	9.
26,	9.16666698,	1.14999998,	9.
27,	9.16666698,	1.25,	8.
28,	9.16666698,	1.14999998,	8.
29,	9.16666698,	1.25,	7.
30,	9.16666698,	1.14999998,	7.
31,	9.16666698,	1.25,	6.
32,	9.16666698,	1.14999998,	6.
33,	9.16666698,	1.25,	5.

34, 9.16666698, 1.14999998, 5.

35, 9.16666698, 1.25, 4.

36, 9.16666698, 1.14999998, 4.

37, 9.16666698, 1.25, 3.

38, 9.16666698, 1.14999998, 3.

39, 9.16666698, 1.25, 2.

40, 9.16666698, 1.14999998, 2.

41, 9.16666698, 1.25, 1.

42, 9.16666698, 1.14999998, 1.

43, 9.16666698, 1.25, 0.

44, 9.16666698, 1.14999998, 0.

45, 8.33333302, 1.25, 10.

46, 8.33333302, 1.14999998, 10.

47, 8.33333302, 1.25, 9.

48, 8.33333302, 1.14999998, 9.

49, 8.33333302, 1.25, 8.

50, 8.33333302, 1.14999998, 8.

51, 8.33333302, 1.25, 7.

52, 8.33333302, 1.14999998, 7.

53, 8.33333302, 1.25, 6.

54, 8.33333302, 1.14999998, 6.

55, 8.33333302, 1.25, 5.

56, 8.33333302, 1.14999998, 5.

57, 8.33333302, 1.25, 4.

58, 8.33333302, 1.14999998, 4.

59, 8.33333302, 1.25, 3.

60, 8.33333302, 1.14999998, 3.

61, 8.33333302, 1.25, 2.

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    62,   8.33333302,   1.14999998,           2.
    63,   8.33333302,         1.25,           1.
    64,   8.33333302,   1.14999998,           1.
    65,   8.33333302,         1.25,           0.
    66,   8.33333302,   1.14999998,           0.
    67,          7.5,         1.25,          10.
    68,          7.5,   1.14999998,          10.
    69,          7.5,         1.25,           9.
    70,          7.5,   1.14999998,           9.
    71,          7.5,         1.25,           8.
    72,          7.5,   1.14999998,           8.
    73,          7.5,         1.25,           7.
    74,          7.5,   1.14999998,           7.
    75,          7.5,         1.25,           6.
    76,          7.5,   1.14999998,           6.
    77,          7.5,         1.25,           5.
    78,          7.5,   1.14999998,           5.
    79,          7.5,         1.25,           4.
    80,          7.5,   1.14999998,           4.
    81,          7.5,         1.25,           3.
    82,          7.5,   1.14999998,           3.
    83,          7.5,         1.25,           2.
    84,          7.5,   1.14999998,           2.
    85,          7.5,         1.25,           1.
    86,          7.5,   1.14999998,           1.
    87,          7.5,         1.25,           0.
    88,          7.5,   1.14999998,           0.
*Element, type=C3D8R
```

1, 23, 24, 26, 25, 1, 2, 4, 3

2, 25, 26, 28, 27, 3, 4, 6, 5

3, 27, 28, 30, 29, 5, 6, 8, 7

4, 29, 30, 32, 31, 7, 8, 10, 9

5, 31, 32, 34, 33, 9, 10, 12, 11

6, 33, 34, 36, 35, 11, 12, 14, 13

7, 35, 36, 38, 37, 13, 14, 16, 15

8, 37, 38, 40, 39, 15, 16, 18, 17

9, 39, 40, 42, 41, 17, 18, 20, 19

10, 41, 42, 44, 43, 19, 20, 22, 21

11, 45, 46, 48, 47, 23, 24, 26, 25

12, 47, 48, 50, 49, 25, 26, 28, 27

13, 49, 50, 52, 51, 27, 28, 30, 29

14, 51, 52, 54, 53, 29, 30, 32, 31

15, 53, 54, 56, 55, 31, 32, 34, 33

16, 55, 56, 58, 57, 33, 34, 36, 35

17, 57, 58, 60, 59, 35, 36, 38, 37

18, 59, 60, 62, 61, 37, 38, 40, 39

19, 61, 62, 64, 63, 39, 40, 42, 41

20, 63, 64, 66, 65, 41, 42, 44, 43

21, 67, 68, 70, 69, 45, 46, 48, 47

22, 69, 70, 72, 71, 47, 48, 50, 49

23, 71, 72, 74, 73, 49, 50, 52, 51

24, 73, 74, 76, 75, 51, 52, 54, 53

25, 75, 76, 78, 77, 53, 54, 56, 55

26, 77, 78, 80, 79, 55, 56, 58, 57

27, 79, 80, 82, 81, 57, 58, 60, 59

28, 81, 82, 84, 83, 59, 60, 62, 61

```
29, 83, 84, 86, 85, 61, 62, 64, 63
30, 85, 86, 88, 87, 63, 64, 66, 65
*Nset, nset=_PickedSet2, internal, generate
 1, 88,  1
*Elset, elset=_PickedSet2, internal, generate
 1, 30,  1
** Section: slab
*Solid Section, elset=_PickedSet2, material="concrete slab"
,
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="slab deck-1", part="slab deck"
          0.,        -0.05,          10.
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      5,  0.119314708, 0.0354203358,           0.
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7, 0.0975364968, 0.0257247165, 0.

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9, 0.18900016, -0.00645989552, 0.

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13, 0.203543201, 0.0233008042, 0.

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16, 0.305000007, -0.0464598946, 0.

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18, 0.170856833, -0.296459883, 0.

19, 0.305131495, -0.296952397, 0.

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90, 0.128196374, -0.0464598946, 4.

91, 0.148606271, -0.311319858, 4.

92, 0.137707621, -0.302341312, 4.

93, 0.0752142742, -0.0253510997, 4.

94, 0.113005921, -0.0262274668, 4.

95, 0.220429733, -0.0273222625, 4.

96, 0.182212055, -0.0354759581, 4.

97, 0.163006678, -0.0183033459, 4.

98, 0.169992879, -0.026244089, 4.

99, 0.14615646, -0.241915196, 4.

100, 0., -0.0464598946, 6.

101, 0., -0.00645989552, 6.

102, 0.0829570666, -0.00645989552, 6.

103, 0.0829570666, 0.0354203358, 6.

104, 0.119314708, 0.0354203358, 6.

105, 0.119314708, 0.0257247165, 6.

106, 0.0975364968, 0.0257247165, 6.

107, 0.0975364968, -0.00645989552, 6.

108, 0.18900016, -0.00645989552, 6.

109, 0.18900016, 0.0336024091, 6.

110, 0.227781609, 0.0336024091, 6.

111, 0.227781609, 0.0233008042, 6.

112, 0.203543201, 0.0233008042, 6.

113, 0.203543201, -0.00645989552, 6.

114, 0.305000007, -0.00645989552, 6.

115, 0.305000007, -0.0464598946, 6.

116, 0.170856833, -0.0464598946, 6.

117, 0.170856833, -0.296459883, 6.

118, 0.305131495, -0.296952397, 6.

119, 0.304984778, -0.33695212, 6.

120, -1.48319114e-05, -0.336459905, 6.

121, -1.48319114e-05, -0.296459883, 6.

122, 0.128196374, -0.296459883, 6.

123, 0.128196374, -0.0464598946, 6.

124, 0.148606271, -0.311319858, 6.

125, 0.137707621, -0.302341312, 6.

126, 0.0752142742, -0.0253510997, 6.

127, 0.113005921, -0.0262274668, 6.

128, 0.220429733, -0.0273222625, 6.

129, 0.182212055, -0.0354759581, 6.

130, 0.163006678, -0.0183033459, 6.

131, 0.169992879, -0.026244089, 6.

132, 0.14615646, -0.241915196, 6.

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134, 0., -0.00645989552, 8.

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148, 0.305000007, -0.0464598946, 8.

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150, 0.170856833, -0.296459883, 8.

151, 0.305131495, -0.296952397, 8.

152, 0.304984778, -0.33695212, 8.

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154, -1.48319114e-05, -0.296459883, 8.

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156, 0.128196374, -0.0464598946, 8.

157, 0.148606271, -0.311319858, 8.

158, 0.137707621, -0.302341312, 8.

159, 0.0752142742, -0.0253510997, 8.

160, 0.113005921, -0.0262274668, 8.

161, 0.220429733, -0.0273222625, 8.

162, 0.182212055, -0.0354759581, 8.

163, 0.163006678, -0.0183033459, 8.

164, 0.169992879, -0.026244089, 8.

165, 0.14615646, -0.241915196, 8.

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167, 0., -0.00645989552, 10.

168, 0.0829570666, -0.00645989552, 10.

169, 0.0829570666, 0.0354203358, 10.

170, 0.119314708, 0.0354203358, 10.

171, 0.119314708, 0.0257247165, 10.

172, 0.0975364968, 0.0257247165, 10.

173, 0.0975364968, -0.00645989552, 10.

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181, 0.305000007, -0.0464598946, 10.

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183, 0.170856833, -0.296459883, 10.

184, 0.305131495, -0.296952397, 10.

185, 0.304984778, -0.33695212, 10.

186, -1.48319114e-05, -0.336459905, 10.

187, -1.48319114e-05, -0.296459883, 10.

188, 0.128196374, -0.296459883, 10.

189, 0.128196374, -0.0464598946, 10.

190, 0.148606271, -0.311319858, 10.

191, 0.137707621, -0.302341312, 10.

192, 0.0752142742, -0.0253510997, 10.

193, 0.113005921, -0.0262274668, 10.

194, 0.220429733, -0.0273222625, 10.

195, 0.182212055, -0.0354759581, 10.

196, 0.163006678, -0.0183033459, 10.

197, 0.169992879, -0.026244089, 10.

198, 0.14615646, -0.241915196, 10.

*Element, type=C3D8R

1, 1, 27, 3, 2, 34, 60, 36, 35

2, 29, 14, 32, 30, 62, 47, 65, 63

3, 10, 9, 14, 13, 43, 42, 47, 46

4, 10, 13, 12, 11, 43, 46, 45, 44

5, 4, 3, 8, 7, 37, 36, 41, 40

6, 6, 5, 4, 7, 39, 38, 37, 40

7, 14, 29, 16, 15, 47, 62, 49, 48

8, 24, 23, 26, 33, 57, 56, 59, 66

9, 25, 20, 19, 18, 58, 53, 52, 51

10, 26, 25, 18, 33, 59, 58, 51, 66

11, 23, 22, 25, 26, 56, 55, 58, 59

12, 22, 21, 20, 25, 55, 54, 53, 58

13, 24, 33, 18, 17, 57, 66, 51, 50

14, 28, 27, 1, 24, 61, 60, 34, 57

15, 24, 32, 31, 28, 57, 65, 64, 61

16, 8, 3, 27, 28, 41, 36, 60, 61

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18, 24, 17, 30, 32, 57, 50, 63, 65

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20, 28, 31, 9, 8, 61, 64, 42, 41

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24, 43, 46, 45, 44, 76, 79, 78, 77

25, 37, 36, 41, 40, 70, 69, 74, 73

26, 39, 38, 37, 40, 72, 71, 70, 73

27, 47, 62, 49, 48, 80, 95, 82, 81

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33, 57, 66, 51, 50, 90, 99, 84, 83

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46, 72, 71, 70, 73, 105, 104, 103, 106

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52, 88, 87, 86, 91, 121, 120, 119, 124

53, 90, 99, 84, 83, 123, 132, 117, 116

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55, 90, 98, 97, 94, 123, 131, 130, 127

56, 74, 69, 93, 94, 107, 102, 126, 127

57, 96, 83, 82, 95, 129, 116, 115, 128

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59, 97, 98, 80, 75, 130, 131, 113, 108

60, 94, 97, 75, 74, 127, 130, 108, 107

61, 100, 126, 102, 101, 133, 159, 135, 134

62, 128, 113, 131, 129, 161, 146, 164, 162

63, 109, 108, 113, 112, 142, 141, 146, 145

64, 109, 112, 111, 110, 142, 145, 144, 143

65, 103, 102, 107, 106, 136, 135, 140, 139

66, 105, 104, 103, 106, 138, 137, 136, 139

67, 113, 128, 115, 114, 146, 161, 148, 147

68, 123, 122, 125, 132, 156, 155, 158, 165

69, 124, 119, 118, 117, 157, 152, 151, 150

70, 125, 124, 117, 132, 158, 157, 150, 165

71, 122, 121, 124, 125, 155, 154, 157, 158

72, 121, 120, 119, 124, 154, 153, 152, 157

73, 123, 132, 117, 116, 156, 165, 150, 149

74, 127, 126, 100, 123, 160, 159, 133, 156

75, 123, 131, 130, 127, 156, 164, 163, 160

76, 107, 102, 126, 127, 140, 135, 159, 160

77, 129, 116, 115, 128, 162, 149, 148, 161

78, 123, 116, 129, 131, 156, 149, 162, 164

79, 130, 131, 113, 108, 163, 164, 146, 141

80, 127, 130, 108, 107, 160, 163, 141, 140

81, 133, 159, 135, 134, 166, 192, 168, 167

82, 161, 146, 164, 162, 194, 179, 197, 195

83, 142, 141, 146, 145, 175, 174, 179, 178

```
 84, 142, 145, 144, 143, 175, 178, 177, 176
 85, 136, 135, 140, 139, 169, 168, 173, 172
 86, 138, 137, 136, 139, 171, 170, 169, 172
 87, 146, 161, 148, 147, 179, 194, 181, 180
 88, 156, 155, 158, 165, 189, 188, 191, 198
 89, 157, 152, 151, 150, 190, 185, 184, 183
 90, 158, 157, 150, 165, 191, 190, 183, 198
 91, 155, 154, 157, 158, 188, 187, 190, 191
 92, 154, 153, 152, 157, 187, 186, 185, 190
 93, 156, 165, 150, 149, 189, 198, 183, 182
 94, 160, 159, 133, 156, 193, 192, 166, 189
 95, 156, 164, 163, 160, 189, 197, 196, 193
 96, 140, 135, 159, 160, 173, 168, 192, 193
 97, 162, 149, 148, 161, 195, 182, 181, 194
 98, 156, 149, 162, 164, 189, 182, 195, 197
 99, 163, 164, 146, 141, 196, 197, 179, 174
100, 160, 163, 141, 140, 193, 196, 174, 173
*Nset, nset=_PickedSet3, internal, generate
  1,  198,    1
*Elset, elset=_PickedSet3, internal, generate
  1,  100,    1
** Section: girder
*Solid Section, elset=_PickedSet3, material=girder
,
*End Instance
**
*Instance, name="cfrp rods-1", part="cfrp rods"
       7.57,        1.17,          10.
```

```
*End Instance
**
*Instance, name="cfrp main-1", part="cfrp main"
        10.,         1.14,        10.01
        10.,         1.14,        10.01,         10.,         0.14,        10.01,          90.
*End Instance
**
*Nset, nset=_PickedSet40, internal, instance="slab deck-1", generate
  1,  88,   1
*Elset, elset=_PickedSet40, internal, instance="slab deck-1", generate
  1,  30,   1
*Nset, nset=_PickedSet41, internal, instance="slab deck-1", generate
  1,  88,   1
*Elset, elset=_PickedSet41, internal, instance="slab deck-1", generate
  1,  30,   1
*Nset, nset=_PickedSet51, internal, instance="slab deck-1", generate
  1,  88,   1
*Nset, nset=_PickedSet51, internal, instance=girder-2
   1,   2,   3,   4,   5,   6,   7,   8,   9,  10,  11,  12,  13,  14,  15,  16
  17,  18,  19,  20,  21,  22,  23,  24,  25,  26,  27,  28,  29,  30,  31,  32
  33,  34,  35,  48,  49,  50,  51,  52,  53,  54,  55,  56,  57,  67,  68,  81
  82,  83,  84,  85,  86,  87,  88,  89,  90, 100, 101, 114, 115, 116, 117, 118
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 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196
 197, 198
*Nset, nset=_PickedSet51, internal, instance=girder-3
   1,   2,   3,   4,   5,   6,   7,   8,   9,  10,  11,  12,  13,  14,  15,  16
```

```
 17,  18,  19,  20,  21,  22,  23,  24,  25,  26,  27,  28,  29,  30,  31,  32
 33,  34,  35,  48,  49,  50,  51,  52,  53,  54,  55,  56,  57,  67,  68,  81
 82,  83,  84,  85,  86,  87,  88,  89,  90, 100, 101, 114, 115, 116, 117, 118
119, 120, 121, 122, 123, 133, 134, 147, 148, 149, 150, 151, 152, 153, 154, 155
156, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180
181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196
197, 198
*Elset, elset=_PickedSet51, internal, instance="slab deck-1", generate
 1,  30,   1
*Elset, elset=_PickedSet51, internal, instance=girder-2
  1,   2,   3,   4,   5,   6,   7,   8,   9,  10,  11,  12,  13,  14,  15,  16
 17,  18,  19,  20,  21,  27,  28,  29,  32,  33,  41,  47,  48,  49,  52,  53
 61,  67,  68,  69,  72,  73,  81,  82,  83,  84,  85,  86,  87,  88,  89,  90
 91,  92,  93,  94,  95,  96,  97,  98,  99, 100
*Elset, elset=_PickedSet51, internal, instance=girder-3
  1,   2,   3,   4,   5,   6,   7,   8,   9,  10,  11,  12,  13,  14,  15,  16
 17,  18,  19,  20,  21,  27,  28,  29,  32,  33,  41,  47,  48,  49,  52,  53
 61,  67,  68,  69,  72,  73,  81,  82,  83,  84,  85,  86,  87,  88,  89,  90
 91,  92,  93,  94,  95,  96,  97,  98,  99, 100
*Elset, elset=__PickedSurf49_S6, internal, instance="slab deck-1", generate
 1,  30,   1
*Elset, elset=__PickedSurf49_S4, internal, instance="slab deck-1", generate
 1,  30,   1
*Surface, type=ELEMENT, name=_PickedSurf49, internal
__PickedSurf49_S6, S6
__PickedSurf49_S4, S4
** Constraint: Constraint-1
*Embedded Element, host elset=_PickedSet40
```

```
"cfrp main-1"."main rod"
** Constraint: Constraint-2
*Embedded Element, host elset=_PickedSet41
"cfrp rods-1"."long side rod"
*End Assembly
**
** MATERIALS
**
*Material, name="cfrp rods"
*Density
1400.,
*Elastic
 4e+08, 0.34
*Plastic
 2.75e+06,    0.
 2.75e+06, 0.017
*Material, name="concrete slab"
*Density
2643.,
*Elastic
31000., 0.2
*Plastic
30.,     0.
30., 0.0035
*Material, name=girder
*Density
2700.,
*Elastic
```

```
 6.4e+08, 0.33
*Plastic
 4e+08,     0.
 4e+08, 0.0017
** ----------------------------------------------------------------
**
** STEP: Load Reaction model
**
*Step, name="Load Reaction model"
*Static
1., 1., 1e-05, 1.
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet51, ENCASTRE
**
** LOADS
**
** Name: Load-1   Type: Pressure
*Dsload
_PickedSurf49, P, 15.
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
```

```
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```

APPENDIX III: SUMMARY OF CFRP PLATFORM FINITE ELEMENT ANALYSIS

Abaqus/Standard 6.10-1 DATE 17-Jul-2014 TIME 07:31:19

SUMMARY OF JOB INFORMATION:

STEP	INC	ATT	SEVERE DISCON ITERS	EQUIL ITERS	TOTAL ITERS	TOTAL TIME/ FREQ	STEP TIME/LPF	INC OF TIME/LPF	DOF MONITOR	IF RIKS
1	1	1	0	1	1	1.00	1.00	1.000		

THE ANALYSIS HAS COMPLETED SUCCESSFULLY

APPENDIX IV: RELIABILITY PROGRAM OF CFRP PLATFORMS IN OFFSHORE

```
PROGRAM  JUNIOR
C    OPTIMISING THE MOMENT RESISTANCE OF CFRP IN FIBRE
C    REINFORCED CONCRETE SLABS
C    X(1)=CONCRETE CHARACTERISTIC STRENGTH
C    X(2)=WIDTH OF SLAB
C    X(3)=EFFECTIVE DEPTH OF SLAB
C    X(4)=IMPOSED LOAD
C    X(5)=SPAN OF SLAB
C    X(6)=TENSILE STRENGTH OF CFRP
C    X(7)=AREA OF CFRP
C    X(8)=MODULUS OF CFRP
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      EXTERNAL BENDING
      DIMENSION  X(8),EX(8),SX(8),VP(10,8),COV(8,8),ZES(3),
     +          UU(8),EIVEC(8,8),IV(2,8)
      CHARACTER*10 PRT
      COMMON/BENDING /ALPHA
      DATA EX/3.0D1,1.0D3,1.5D2,1.0D1,1.85D3,2.25D3,6.42D1,1.5D5/,
     +    SX/4.5D0,5.0D1,6.846D1,2.0D0,5.5D1,6.75D1,1.4D1,4.41D0/,
     +    N/8/,NC/8/,NE/8/,IRHO/1/
      WRITE(*,*)'ENTER VALUES FOR ALPHA.......'
      READ(*,*)ALPHA
      WRITE(*,*)'INPUT VALUE OF STRENGTH OF CFRP...'
      READ(*,*)EX(6)
      SX(6)=0.03*EX(6)
```

```
      WRITE(*,*)'INPUT VALUE OF EFFECTIVE DEPTH...'
      READ(*,*)EX(3)
    SX(3)=0.03*EX(3)
    NAUS=7
    ICRT=0
    OPEN(7,FILE='JUNIOR.RES',STATUS='OLD',ERR=10)
    GOTO 20
10   OPEN(7,FILE='JUNIOR.RES',STATUS='NEW')
20   CALL YINIT (N,IV,VP,IRHO,COV,NC)
    IV(1,1)=3
    IV(1,6)=9
    IV(1,8)=9
    IV(1,4)=7
    DO 100 I=1,N
100      X(I) = EX(I)
    CONTINUE
      V1=0.25D0
    BETA=1.D0
    WRITE (NAUS,5000)
5000  FORMAT (////,5X,70('*'),/,30X,'F O R M 5',/,5X,70('*'),/,
   +   20X,'SAFETY LEVEL BENDING CHECK ON JUNIOR')
    CALL YKOPF (NAUS, N, IV, EX, SX, VP, IRHO)
    WRITE (ICRT,*) ' START OF FORM5'
    WRITE (ICRT,*) ' STOCHASTIC MODEL :'
    CALL YKOPF (ICRT, N, IV, EX, SX, VP, IRHO)
    PRT='  COV  '
    CALL YMAUS (NAUS,NC,N,COV,PRT)
    CALL FORM5 (N, IV, EX, SX, VP, BENDING, IRHO, COV, NC,
```

```
     +          EIVEC, NE, V1, NAUS, BETA, X, UU, ZES, IER)
      PRT='  UU  '
      CALL YFAUS (NAUS,N,UU,PRT)
      PRT='  ZES  '
      CALL YFAUS (NAUS,3,ZES,PRT)
        WRITE(NAUS,504)
       write(NAUS,505)(uu(i)/beta,i=1,n)
504     FORMAT(/,3X,'ALPHA VECTOR:')
505     format(3x,/3X,6(2X,E8.2)/)
      WRITE (ICRT,*) ' END OF FORM5 : IER =',IER
      WRITE (ICRT,*) ' RESULTS SEE FILE AKACHI.RES'
      STOP
      END
      SUBROUTINE BENDING (N, X, FX, IER)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(N)
      COMMON /BENDING/ALPHA
C         G(X) = R-S
      A1=X(3)
      A2=0.0128*X(8)*X(7)
      A3=1.105*X(1)*X(2)-0.002*X(1)**2*X(2)
      R=0.75*X(6)*X(7)*A1-A2/A3
      S= 0.125*X(4)*X(5)**2*(1.25*ALPHA+1.5)
C         CHECK FOR ERRORS, CALCULATE FX
      IF (R.NE.0..AND.S.NE.0)THEN
         FX = R-S
        IER = 0
      ELSE
```

```
  FX = 1.D+20
  IER = 1
ENDIF
RETURN
END
```

APPENDIX V: TABLES OF ANALYSIS OF SAFETY RESULTS

Table 4.11:Safety Index Values for f_{fpu} of 1500N/mm^2;   (L = 1850mm, f_{ck} = 30N/mm^2)

d \ α	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	0.104	-0.453	-0.885	-1.29	-1.67	-2.03	-2.37	-2.70	-3.01	-3.31
125	0.727	0.307	0.0885	-0.453	-0.801	-1.13	-1.44	-1.74	-2.03	-2.31
150	1.26	0.875	0.513	0.173	-0.148	-0.453	-0.744	-1.02	-1.29	-1.55
175	1.68	1.32	0.982	0.665	0.365	0.11	-0.193	-0.453	-0.704	-0.944
200	2.01	1.68	1.36	1.06	0.782	0.513	0.256	0.104	-0.226	-0.453
225	2.29	1.97	1.68	1.40	1.13	0.875	0.631	0.398	0.173	-0.043

250	2.51	2.22	1.94	1.70	1.42	1.18	0.95	0.727	0.513	0.307

Table 4.12: Safety Index Values for f_{fpu} of 1750N/mm^2; (L = 1850mm, f_{ck} = 30N/mm^2)

α / d	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	0.513	0.079	-0.324	-0.704	-0.106	-1.40	-1.72	-2.03	-2.33	-2.61
125	1.18	0.790	0.424	0.0796	-0.246	-0.555	-0.849	-1.13	-1.40	-1.66
150	1.68	1.32	0.982	0.665	0.365	0.079	-0.193	-0.453	-0.704	-0.944
175	2.06	1.73	1.42	1.12	0.844	0.578	0.323	0.079	-0.155	-0.380
200	2.37	2.06	1.77	1.50	1.23	0.982	0.743	0.513	0.292	0.0796
225	2.61	2.33	2.06	1.80	1.56	1.32	1.09	0.875	0.665	0.436
250	2.82	2.56	2.31	2.06	1.83	1.60	1.39	1.18	0.982	0.790

Table 4.13: Safety Index Values for f_{fpu} of 2000N/mm^2; (L = 1850mm, f_{ck} = 30N/mm^2)

α / d	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	0.922	0.513	0.132	-0.226	-0.564	-0.885	-1.19	-1.48	-1.76	-2.03
125	1.55	1.18	0.837	0.513	0.206	-0.10	-0.363	-0.63	-0.885	-1.13
150	2.01	1.68	1.36	1.06	0.782	0.513	0.256	0.014	-0.226	-0.453
175	2.37	2.06	1.77	1.50	1.23	0.982	0.627	0.513	0.292	0.10
200	2.65	2.37	2.10	1.84	1.60	1.36	1.14	0.922	0.714	0.513
225	2.87	2.61	2.37	2.13	1.90	1.68	1.47	1.26	1.06	0.875
250	3.05	2.82	2.59	2.27	2.15	1.94	1.74	1.55	1.36	1.18

Table 4.14: Safety Index Values for f_{fpu} of 2250N/mm^2; (L = 1850mm, f_{ck} = 30N/mm^2)

α / d	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	1.26	0.875	0.513	0.173	-0.148	-0.453	-0.744	-1.02	-1.29	-1.55
125	1.85	1.51	1.18	0.875	0.584	0.307	0.10	-0.21	-0.454	-0.687
150	2.29	1.97	1.68	1.40	1.13	0.875	0.631	0.398	0.173	-0.10
175	2.61	2.33	2.06	1.80	1.50	1.32	1.09	0.875	0.665	0.463
200	2.87	2.61	2.37	2.13	1.90	1.68	1.47	1.26	1.06	0.875
225	3.07	2.84	2.61	2.39	2.18	1.97	1.78	1.58	1.40	1.22
250	3.23	3.02	2.82	2.60	2.42	2.22	2.04	1.85	1.68	1.51

Table 4.15: Safety Index Values for f_{fpu} of 2500N/mm^2; (L = 1850mm, f_{ck} = 30N/mm^2)

α / d	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	1.55	1.18	0.837	0.513	0.206	-0.10	0.363	-0.63	-0.885	-1.13
125	2.11	1.78	1.47	1.18	0.91	0.641	0.388	0.147	0.185	-0.309
150	2.51	2.22	1.94	1.68	1.42	1.18	0.95	0.727	0.513	0.307
175	2.82	2.56	2.31	2.06	1.83	1.60	1.39	1.18	0.982	0.79
200	3.05	2.82	2.59	2.37	2.15	1.94	1.74	1.55	1.36	1.18
225	3.23	3.02	2.82	2.61	2.42	2.22	2.04	1.85	1.68	1.51
250	3.38	3.19	3.00	2.82	2.64	2.46	2.28	2.11	1.94	1.78

Table 4.16: Safety Index Values for f_{fpu} of 2750N/mm^2; (L = 1850mm, f_{ck} = 30N/mm^2)

α / d	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2.0
100	1.80	1.45	1.12	0.807	5.13	0.234	-0.133	-0.289	-0.534	-0.770
125	2.33	2.02	1.73	1.45	1.18	0.929	0.688	0.456	0.234	0.191
150	2.71	2.43	2.17	1.92	1.68	1.45	1.23	1.01	0.807	0.610
175	2.99	2.75	2.51	2.28	2.06	1.85	1.64	1.45	1.26	1.07
200	3.20	2.99	2.78	2.57	2.37	2.17	1.98	1.80	1.62	1.45
225	3.36	3.18	2.99	2.80	2.61	2.43	2.26	2.09	1.92	1.76
250	3.49	3.33	3.16	2.99	2.82	2.65	2.49	2.33	2.17	2.02

APPENDIX VI