Experimental research on strengthening of concrete beams by the use of epoxy adhesive and cement-based bonding material

by

Sólrún Lovísa Sveinsdóttir

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Supervisors:

Dr. Ólafur H. Wallevik
Professor, Reykjavik University, Iceland
Professor (adjunct), Sherbrooke University, Canada

Jón Guðni Guðmundsson
Ph.D. Engineering student at Reykjavik University, Iceland

Examiner:

Dr. Jónas Þór Snæbjörnsson
Professor, Reykjavik University, Iceland

ABSTRACT

Fibre reinforced polymer (FRP), as externally bonded reinforcement, is a very beneficial technique to repair and strengthen reinforced concrete (RC) members. This technique is used in a number of applications to increase the shear capacity of structural beams. This feature is achieved by applying e.g. basalt fibre reinforced polymer (BFRP) that is glued to the RC concrete member with an adhesive. The most common adhesive used for strengthening is epoxy. There are some limitations with the use of epoxy adhesives, including poor fire resistance. Therefore, other adhesive was used to strengthen concrete beams in flexure. Cement-based bonding material would be beneficial to produce strengthening system that is fire resistant, also it significantly lower the cost of retrofitting on existing structures.

An experimental investigation was conducted on shear behaviour of RC beams that are strengthened using BFRP external reinforcement with epoxy resin as bonding agent. This experimental test program is set up to test the shear capacity of beam specimens. For the analytical verifications, ACI 440 guideline and TR55 guideline was used to verify the influence of externally bonded FRP reinforcement. The experimental investigation was conducted in two phases and consisted of 14 full-scale ordinary RC concrete beams, 5 of them were used as reference beams and the remaining 9 were strengthened with BFRP sheets. Phase three is an experimental investigation conducted on 8 full-scale ordinary RC concrete beams strengthened in flexure with a cement-based bonding material.

The shear testing conducted has shown that by shear strengthening RC beam with external FRP reinforcement using epoxy adhesive, the load carrying capacity can be increased. The experimental results did compare well to the calculations based on standards, but overall the use of BFRP resulted in increased shear capacity.

The flexural testing conducted showed that excellent bonding properties can be achieved by using several types of cement-based bonding material. The mixtures generally included Portland cement with silica fume (SF) to increase strength and super plasticizer (SP) to reduce the water content and to achieve the workability. Three different mixtures were used, including silica fume (SF), super plasticizer (SP), synthetic micro fibres and acryl.

Two design models available in current design guidelines were used to compute the BFRP effective strain and the shear contribution to the shear load carrying capacity of the BFRP shear strengthened beams. The experimental results were compared to analytical results for both shear and flexural strengthening.

Keywords: Reinforced concrete beam, FRP strengthening, BFRP strengthening, shear, flexure, cement-based bonding.

ÁGRIP

Steinsteypt mannvirki krefjast reglulegs viðhalds til að tryggja að áætlaður endingartími mannvirkisins standist. Það lofar góðu að nota trefjastyrkt viðloðunarefni (FRP) til viðgerðar eða styrkingar á steinsteyptum mannvirkjum. Þessi aðferð hefur verið notuð víða til að auka burðargetu steinsteyptra mannvirkja. Hægt er að ná fram aukinni burðargetu í steinsteyptum mannvirkjum með því að nota FRP með basalttrefjum (BFRP). Trefjaefnið er því utan á liggjandi styrking fyrir mannvirkið. Algengasta viðloðunarefnið er epoxý lím en það hefur takmarkanir til að mynda lágt brunaþol. Því var annað viðloðunarefni einnig skoðað til styrkingar á steinsteypu. Múr getur verið góður kostur til trefjastyrkingar til að fá aukið brunaþol og einnig til að lágmarka kostnað til viðgerðar eða styrkingar á steinsteyptum mannvirkjum.

Rannsókn var gerð til að kanna sker-hegðun á járnbentum steinsteyptum bitum sem voru styrktir með BFRP þar sem epoxý viðloðunarefni er notað. Uppsetning rannsóknar var gerð þannig að skerþol bitanna var áætlað. Rannsóknin fyrir sker-hegðunina var framkvæmd í tveimur hlutum, í heildina voru fjórtán steinsteyptir bitar, fimm af þeim voru óstyrktir og hinir níu voru styrktir með BFRP. Hönnunarstaðlarnir ACI 440 og TR55 eru kynntir og styrktaraukning útreikninganna eru bornar saman við niðurstöður rannsóknar.
Þriðji hluti rannsóknarinnar var gerður til að kanna vægiþol á steinsteyptum bitum sem voru styrktir með BFRP þar sem múr var notaður sem viðloðunarefni. Sá hluti innhélt átta steinsteypta bita, tveir voru óstyrktir og hinir sex voru styrktir með mismunandi tegundum af múr.

Niðurstöður skerþolsrannsóknarinnar sýndi að með því að styrkja steinsteypta bita með BFRP má auka skerþol steypunnar gagnvart skerálagi. Niðurstöður rannsóknanna bar heim og saman við útreikningar úr hönnunarstöðlum en auðséð er að með notkun BFRP næst fram aukið skerþol.

Niðurstöður vægiþolsrannsóknarinnar sýndu að með því að múr-styrkja steinsteypta bita með BFRP má auka vægiþol steypunnar gagnvart þveráraun. Með næstum öllum múrtegundunum sem gerðar voru mátti sjá aukið vægiþol. Allar múrblöndurnar innihéldu Portland sement, kýsilryk til að auka styrk múrsins og flotefni sem var notað í þeim tilgangi til að minnka vatnsmagnið og ná fram góðum vinnanleika. Mismunur þessara þriggja múrblandna var aukið magn kýsilryks, minna magn af flotefni, tilbúnar ör trefjar og akrýl. Niðurstöður hönnunarstaðlanna sýndu viðunandi nákvæmni á auknu vægiþoli.

Lykilorð: Járnbent steinsteypa, trefjastyrking, basalttrefjar, múr.

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NOTATION AND SYMPOLS

Abbreviations

FRP	=	Fibre reinforced polymers
AFRP	=	Aramid fibre reinforced polymers
BFRP	=	Basalt fibre reinforced polymers
CFRP	=	Carbon fibre reinforced polymers
GFRP	=	Glass fibre reinforced polymers
RC	=	Reinforced concrete
CBM	=	Cement-based material

Roman upper case symbols

A_c	=	Area of concrete (mm^2)
A_f	=	Area of FRP (mm^2)
E_c	=	Modulus of elasticity of concrete (GPa)
E_f	=	Modulus of elasticity of FRP (GPa)
G	=	Bulk modulus (GPa)
K_m	=	Bond-dependent coefficient
L	=	Distance between supports (mm)
L_f	=	Length of the FRP longitudinal reinforcement (mm)
M	=	Flexure load capacity (kNm)
M_u	=	Flexural load capacity of beam at ultimate (kNm)
V_c	=	Shear strength of concrete (kN)
V_f	=	Shear contribution of FRP (kN)
Ø	=	Diameter of reinforcement bar (mm)

Roman lower case symbols

a	=	Shear span (mm)
b	=	Width of beam (mm)
h	=	Height of beam (mm)
d_{cover}	=	Concrete cover (mm)
d	=	Effective depth (mm)
f_c	=	Compressive strength of concrete (MPa)
f_y	=	Yield strength of steel (MPa)
f_f	=	Tensile strength of FRP (MPa)

f_s	=	Stress level in the steel reinforcement (MPa)
f_{fe}	=	Effective tensile stress in FRP (MPa)
k_1	=	Modification factor
k_2	=	Modification factor for U-wrapped systems
k_v	=	Strain-reduction factor
t_f	=	Thickness of FRP (mm)
n	=	Number of layers
s_f	=	Width of FRP (mm)
x	=	Depth of neutral axis (mm)
z	=	Neutral axis (mm)

Greek symbols

ε_f	=	Tensile strain (%)
ε_{fe}	=	Effective strain in FRP (%)
ε_{fe}	=	Strain in concrete (%)
ε_{es}	=	Existing strain in the concrete (%)
ν	=	Poissons ratio
ρ_f	=	FRP reinforcement ratio (%)
ρ	=	Steel reinforcement ratio (%)
β	=	Fibre alignment (°)
β_1	=	Equivalent rectangular stress block

1 INTRODUCTION

1.1 Background

Fibre reinforced polymer (FRP) is a composite material made of fibres that have high strength and adhesive that binds the fibres together to fabricate the structural material. Commonly used fibre types are aramid, carbon and glass, basalt fibres are relatively new in the civil engineering industry. The adhesive that is commonly used is epoxy. FRP was originally developed for aircraft, ships and high-speed trains, because of the beneficial advantages like low weight and resistance to environmental factors this was considered to be beneficial application for these producers [1].

In the 1980s, the use of FRP to strengthen civil engineering structures started [1, 2]. Even though it has been used for a short time large number of projects have been carried out. It was discovered that the FRP strengthening technique is suitable for structural repair and retrofitting of existing structures. Several concrete structures are facing durability problems, such as environmental factors, increased load and corrosion [3]. Therefore, FRP system that is non-metallic material is considered to be a beneficial technique, due to e.g. FRP has more durability. The most practical solutions for repairing and retrofitting structures to resist higher design loads and other durability problems can be accomplished by using FRP. FRP composites is one of the latest development in the civil engineering industry, there are many others traditional techniques available like externally bonded steel plates, steel or concrete jackets and external post tensioning [4].

Concrete beams are important elements in structural engineering. Like all other concrete elements they are vulnerable for situations where there is an increase in structural capacity. Generally reinforced concrete (RC) beams fail in two ways: flexural failure and diagonal tension (shear) failure. In nature the shear failure is more sudden and brittle [5]. It gives no warning prior to failure except for large cracks and it is more dangerous than flexural failure. The main purpose of this experimental work is to investigate and understand the behaviour of the relatively new basalt fibres reinforced polymer (BFRP) by external strengthening RC beams for flexure and shear. The main advantages of FRP materials are their lightweight, high strength and stiffness, resistance to corrosion and flexibility. The main disadvantages are their low fire resistance and low glass transition temperature.

Shear strengthening of RC beams using FRP with the bonding agent epoxy has been studied intensively for more than a decade, both theoretically and experimentally. In the experimental work engineers have been focusing on the commonly used fibres, aramid (AFRP), carbon (CFRP) and glass (GFRP). Basalt (BFRP) is a relative new FRP composite compared to the commonly used fibres. The basalt fibres are manufactured from a basalt rock in a single process, there are no additives in basalt finer manufacturing. The studies so far are far from sufficient but some studies demonstrate the advantages as well as the high performance of BFRP in structural strengthening. Among the commonly used fibres BFRP is more similar to GFRP than CFRP, according to Table 3 [1,6].

Shear in concrete has always been a challenge for researchers to understand. The shear behaviour and shear strength of reinforced concrete elements has been studied for more than 100 years. The problem is that it is difficult to predict accurately the shear failure e.g. in simple concrete beams, more properly called “diagonal tension failure”. This is a problem that has generated a lot of debates for researchers and engineers for many years. The past years, models and methods have been suggested to describe and to predict shear failure and shear strength. [7,8].

Numerous experimental studies on shear strengthening of RC beams with FRP composites have been carried out by Chaallal, Triantafillou, Khalifa, Chen and Teng and Denton [9–11]. All of these studies show results that led to several design equations and analytical models that are adopted by design codes. These results predict the shear contribution of FRP composites.

Flexure in beams strengthened with basalt FRP reinforcement with cement-based material as bonding agent has been recently proposed to reduce or overcome the epoxies disadvantages that were mentioned here above. Cementitious matrix exhibits significant heat resistance and it can be applied at a low temperature and on surfaces that are wet. This kind of a composite material is usually identified in the technical literature as textile-reinforced mortar (TRM) or fibre-reinforced cement (FRC).

Numerous experimental studies where strengthening of RC beams with FRP composites as well as cement-based material as a bonding agent have been carried out for instance by Triantafillou and Papanicolau, Angelo and Francesco, Siavash as well as Riadh and Hashemi and Al-Mahaidi [12–15]. All of these studies showed results that led to an increase in load carrying capacity and thereby, using cement based material, is an efficient way to increase the load carrying capacity and creating a more fire resistance because the epoxies cannot withstand temperatures above 50°C and by using cement-based bonding material is one way of creating environmentally friendly strengthening system.

In this thesis two different analytical models will be presented for shear strengthening. Both of them will estimate the maximum allowable capacity in the external BFRP reinforcement in the experimental beams. These design guides are the American Concrete Institute (ACI 440) which is based on research by Khalifa et al 1998 and the Concrete Society in the UK (TR55) which is based on research proposed by Denton et al. 2004 [2,16].

1.2 Statement of this investigation

The service life of a concrete structure is often shorter than planned. This is mainly due to the environmental actions that may occur. Because of the high strength of the material and good protection from environmental agents, the use of advanced BFRP as structural reinforcement is a promising alternative, especially as externally bonded reinforcement for concrete structures.

Strengthening of concrete structures using BFRP external reinforcement is an interesting topic, because studies of flexural strengthening with cement-based material as a bonding agent are relatively new and therefore it is interesting to investigate the suitability of using cement based material as bonding agent. Also studies of shear strengthening of RC beams by the use of composite materials is relatively new in the marked and has not been clearly demonstrated. In this case, a full-scale test will be performed to demonstrate the actual behaviour of the retrofitted structure. It can lead to a better understanding of the performance of the system as a whole.

1.3 Research objectives and aim of the study

The overall aim of this research is to investigate and gather knowledge on RC beam elements shear strengthened with externally bonded BFRP reinforcement and to investigate the suitability of using cement-based material as bonding agent in strengthening of existing RC beam.

The main objectives of this research are:

- To study the basis of BFRP strengthening.
- To study the structural behaviour of RC beam elements using externally bonded BFRP reinforcement.
- To evaluate and analyze the shear capacity of RC beams strengthened with externally bonded BFRP reinforcement.
- To compare standard design calculations to the experimental results.
- To investigate the suitability of cement-based material as a bonding agent.
- To research the structural behaviour of RC beam element flexure strengthened with BFRP reinforcement with cement-based material as a bonding agent.

1.4 Research approach

To achieve the goals that are mentioned here above an organized step by step procedure has to be used. This thesis will represent both a literature review and review of the experimental work that was done.

It is important to understand the main objectives of the research. This work was done through literature survey that was conducted online in databases that Reykjavik University recommended, such as Google scholar, Pro Quest, Science Direct and Web of Science. Also the library at Reykjavik University and the library of University of Iceland came in handy. Literature for research similar to BFRP shear strengthening as well as strengthening with cement-based bonding material was not easy to find. That is understandable as this material is relatively new in the civil engineering industry. Therefore the outline of the thesis will be more generally about FRP.

Experimental work was finalized based on the extensive literature review. In this part it is important that the existing analytical models are accurate so they can predict the shear and flexural capacity of a strengthened beams.

2 STATE OF THE ART

2.1 Introduction

This chapter provides an introduction to fibre reinforced polymer (FRP) materials as external reinforcement to strengthen existing structures. The use of FRP as a structural reinforcement in the civil engineering industry, FRP as reinforcement for strengthening and repairing and the advantages and disadvantages of this technique will be discussed briefly. The material characteristics of FRP reinforcement, epoxy resin and cement-based material (CBM) as composite material will be covered. Finally, the material mechanical properties and the shear mechanism will be discussed as well as structural issues that engineers should be aware of.

2.2 FRP composites as structural reinforcement

2.2.1 General information on FRP composites

FRP has been available in many forms so it can be used as a structural reinforcement for concrete elements. Sheets, bars and mesh are some of these forms that are used like shown in Figure 2-2. In existing structures that need strengthening or have to be repaired, FRP sheets are usually used. Composite materials like sheets have different shape, surface texture, and configurations. The fibres can be placed in multiple directions as shown in Figure 2-1. Epoxy resin or cement-based bonding material can be used with different types of fibres: AFRP (Aramid Fibre Reinforced Polymers), CFRP (Carbon Fibre Reinforced Polymer), GFRP (Glass Fibre Reinforced Polymer) or BFRP (Basalt Fibre Reinforced Polymer). Therefore, FRP reinforcement forms a group of products where the characteristics are not the same and many reinforcement types can be used in different situations [1,17].

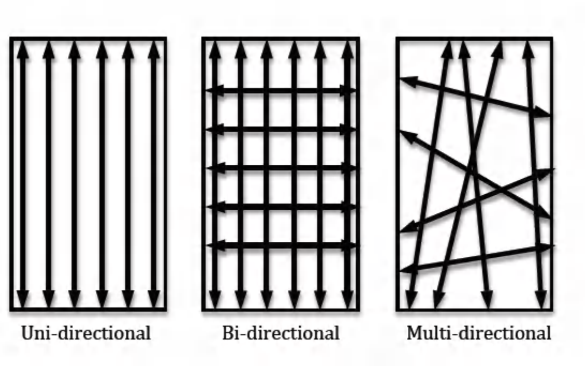

Figure 2-1. Fibre directions in composite materials like sheet.

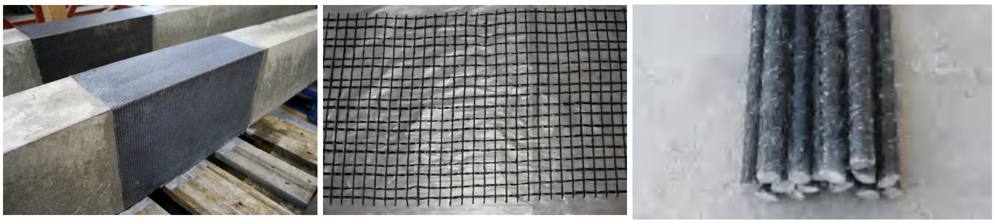

Figure 2-2. Various forms of FRP materials. From left: sheets, mesh and bars [17,18].

Typical stress-strain behaviour for FRPs along with reinforcing steel is shown in Figure 2-3. The FRP does not experience any yielding during tension, it has a linear elastic behaviour from the origin (starting point) up to failure where the ultimate stress is reach. Steel normally has higher modulus of elasticity than FRP element, but FRPs are characterized by high tensile strength in the range of 2400 to 5400 MPa [1,16,17,20,21]. More details on the characteristics of FRP materials are given in Chapter 2.4.

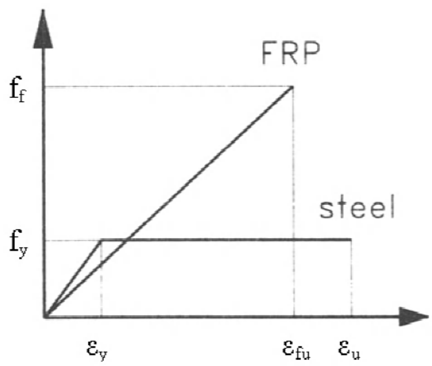

Figure 2-3. Stress-strain behaviour of FRP compared to steel [22].

2.3 FRP as structural reinforcement for structural engineering

2.3.1 Strengthening with FRP sheets

The layup technique, where FRP sheets are placed on e.g. concrete element and fixed externally usually with epoxy resin, is gaining wide acceptance in structural engineering because of its advantages. FRP materials are non-metallic and are more likely to be resistant to aggressive chemicals, therefore they are good option for reinforcement of concrete structures. By means of structural strengthening the bearing capacity can be increased. If the service life of a structure is shorter than anticipated, investments related to maintaining the structure can be justified. The maintenance can be categorized into two types, repair (retrofit) and strengthening (upgrading) of a certain structure [23]. Strengthening with FRP sheets has shown to be a beneficial alternative to structural elements that have had a change in function. It has been shown from past studies that FRP sheets can be used to enhance the capacity of both flexural and shear as shown in Figure 2-4. Due to the flexible nature of FRP sheets they are found to be a good retrofitting alternative for concrete structures in earthquake areas. By means of repairing (retrofitting), durability is the most urgent need in the repair of concrete structures. Concrete structure can deteriorate due to environmental actions like steel corrosion, freeze-thaw, alkali-silica reaction, fire etc. [1,17,24].

Figure 2-4. Shear and flexure strengthened beam [25].

2.3.2 Advantages and disadvantages of FRP materials

The advantages and disadvantages of FRP materials can be seen in Table 1 and Table 2. The tables as presented are a collection of relevant points from sources [1,17].

Table 1. The advantages of FRP materials.

Advantages
• High ultimate strength (2-3 times greater than steel)
• Lower density than steel
• Strength to weight ratio is higher than for steel
• Handling and installation is significantly easier than for steel
• Requires little maintenance
• Excellent durability
• Excellent corrosion resistance
• Good flexibility

Table 2. The disadvantages of FRP materials.

Disadvantages
• High cost
• Long-term durability is not yet avalible
• Risk of fire or accidential damage (unless the FRPs are protected)
• Low modulus of elasticity
• The transverse strength is low

2.4 Material characteristics

2.4.1 Basalt fibres

Basalt fibre is a unique product made from volcanic material deposit, basalt rock. The basalt fibres go through a melting process where the basalt rocks are divided into small particles so it can form fibres. The production of basalt fibres is a single process. The fibres do not contain any other additives in the production, which makes advantages in cost compared with other commonly used fibres.

Basalt has excellent strength, durability and thermal properties. Sim, Park and Moon from Hanyang University in South Korea have studied the durability and mechanical properties of basalt fibres, carbon and high strength S-glass fibres [26]. The basalt fibres used were manufactured in Russia and had the tensile strength of 1000 MPa, which is about 30% of the strength of carbon fibres and 60% of high strength S-glass fibres. Alkali-resistance was examined and the results where measured after 7, 14, 21 and 28 days after having been lying in 1 M alkali solution. The results showed that the basalt and high strength S-glass lost their tensile strength but the carbon fibre did not show significant strength reduction. Accelerated weathering test was also examined where the basalt fibre was found to have better resistance than the high strength S-glass fibre. The tensile strength of the fibres was examined after they had been placed in high-temperature oven at 100, 200, 400 and 600°C for 2 hours, the basalt fibres kept about 90% of their strength which shows good thermal stability. Carbon and high strength S-glass fibres started to lose their strength at 200°C.

In Table 3 the mechanical properties of different types of fibres can be seen [1,12]. It can easily be seen that the basalt fibres have high tensile strength as well as high ultimate tensile strain that makes strengthening a good option, e.g. enhancing seismic performance. More about seismic behaviour in section 2.5.2.

Table 3. Fibre mechanical properties.

Fiber	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate tensile strain (%)	Unit weight (g/cm^3)
Carbon HS	4300-4900	230-240	1.9-2.1	1.8
Carbon HM	2740-5490	294-329	0.7-1.9	1.78-1.81
Carbon UHM	2600-4020	540-640	0.4-0.8	1.91-2.12
Aramid	3200-3600	124-130	2.4	1.44
Glass	2400-3500	70-85	3.5-4.7	2.6
Basalt	2500	84	3.15	2.6

2.4.2 Adhesives

By means of an adhesive, two materials are needed, e.g. FRP and concrete to connect to each other so that full composite action can be developed. When using the FRP strengthening or repair technique, the adhesive is used to glue the two materials together. Also it provides a load path between these two materials.
The use of adhesives in structural industry continues to develop. Adhesives are based up on the composition to meet certain requirements for the industry like high elastic modulus, high strength, bond quality and workability. Also durability should be considered therefore, adhesive should exhibit low creep, thermal stability and resistance to moisture and alkaline nature. Most widely used and accepted as structural adhesives are epoxies. Cement-based materials are a good alternative as an adhesive because there are some drawbacks with the use of epoxy adhesives in certain areas, such as where fire resistance is important [27].

2.4.2.1 Epoxy as a structural adhesive

Fibre composites used in the structural industry contain a matrix of thermosetting resins that can be epoxy, vinylester or polyester. The most used and favourable matrix is considered to be epoxy. The selection of the matrices type to be used in structural application is governed by various factors including environment and the speed of fabrication.
Epoxy resin is formed from two different chemicals, an epoxide “resin” with polyamine “hardener”. The most widely used epoxy resin in the structural industry is diglycidyl ether of bisphenol A (DGEBA). It may also include dilulants to reduce viscosity and flexibilizers to improve impact strength of the cured epoxy [17]. Due to the input materials, epoxy resins have a very wide range of mechanical and physical properties. Their main advantages for the structural industry is to offer high surface activity, high cohesion and adhesion, low shrinkage and low creep. The major disadvantage of epoxy resin is a relatively high cost, long curing time as well as the unavoidable fire resistance. Table 4 shows the mechanical properties of different adhesives [1,16-17].

Table 4. Mechanical properties of adhesives.

Materials	Tensile strength (Mpa)	Tensile modulus (GPa)	Failure strain (%)	Density (g/cm^3)
Polyester	40-90	2-4.5	1-4	1.10-1.46
Vinylester	70	3	5	1.2
Epoxy	30-100	2-5	3-6	1.11-1.40

2.4.2.2 Cement-based material as structural adhesives

The development of cement-based materials has been fruitful in the last years. It is important that new materials and technologies appear on the market so it can fulfil the further need of repair and strengthening applications in the structural industry.
When it comes to cement-based materials it can be complex. To meet up with expectations the cement-based materials have excellent properties, not only, the strength bonding but also to achieve good workability. A cement-based bonding system is logically used to bond the fibre composite to the structure and the FRP sheet is there to resist the stresses in the strengthening structure. By replacing the epoxy resin with cement-based material, all the epoxies resins problems would be resolved, their poor behaviour above the glass transition temperature (is the transition in material from a relatively brittle state into molten state) and high cost [24,25].
One of the features of cement-based bonding material is the importance of their chosen constituents. In the following sections a description on the most common constituents for binders can be found. A cement-based strengthening system depends on the use of the binder.

2.4.2.2.1 Minerals

The minerals that are used in cement-based materials are the same as the minerals that are used in concrete. Examples of these materials can be ordinary Portland cement, fly ash, silica fume etc. The most common technique is to mix these minerals and add some fine grade aggregates <2 mm [30].

2.4.2.2.2 Additives

To enhance the properties of cement-based material additives can be added in form of super plasticizers. Adding super plasticiser to the mixture the workability, durability and the strength of the cement-based binder can be improved.

2.4.2.2.3 Micro fibre reinforcement

Concrete and cement-based materials are considered to be brittle materials as they have low tensile strength and failure strain. In order to obtain high performance cement-based materials for application such as strengthening, micro fibre reinforcement can effectively improve the mechanical behaviour [25,26]. Different types of fibres can be used, such as, steel, basalt, polypropylene, synthetic micro fibres and natural fibres.

2.5 Structural Issues

2.5.1 Environments

All engineering structures are subjected to mechanical deterioration with time, load and exposure to harmful environments. When FRPs are used to strengthen or repair concrete structures, they can be expected to be exposed to harmful physical and chemical environments.

The main load-carrying element in FRP composite are fibres, to provide the strength and stiffness of the FRP composite. The overall durability depends on the properties of the matrix that protects the fibres from damage as shown in Figure 2-5 [24].

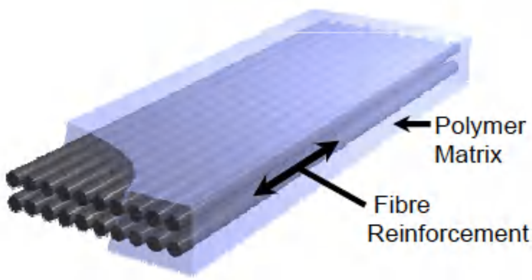

Figure 2-5. Combination of fibres and matrix to form an FRP composite [24].

FRP materials are very durable and are considered to be less susceptible to harmful environments than other construction material. There are some different environmental conditions that affect durability, these environmental and physical conditions are shown in Table 5 [13,17]. A definition offered by Karbhari [24], for the material to be durable it has to resist:

> "cracking, oxidation, chemical degradation, delimitation, wear, and/or the effects of foreign object for a specified period of time under the appropriate load conditions, under specified environmental conditions."

Table 5. Environmental and physical effects on durability of FRP composites.

- Water (sea water) - Mosture and Marine environments
- Chemical solutions - Alkalinity and corrosion
- Thermal cycling - Freeze-thaw
- Fire
- Ultraviolet Radiation
- Creep and relaxation
- Fatique

2.5.2 Seismic behaviour

Concrete beams are load bearing structural elements that can be used to carry both vertical gravitational forces and horizontal loads (i.e. loads due to an earthquake (seismic load or wind). Beams are defined as the horizontal member of the structure. Beams carry all vertical loads and transmit them to the columns or walls of the structure. When earthquakes happen it generates a ground motion both in horizontal and vertical directions. Due to the inertia of the structure the ground motion generates shear forces and bending moment in the structure.

Recent earthquakes have reminded us of how vulnerable structures really are. The performance of structures can be improved by strengthening them in future earthquakes. There is a large number of existing structures worldwide that need to be repaired and strengthened (retrofitting) because of damage due to earthquakes. The main objective of the structural element retrofitting is to strengthen and to eliminate changes in the structure. Where FRP composites are used as external reinforcement to strengthen or repairing concrete elements like beams, it will increase the strength (ultimate limit state) and the stiffness (serviceability limit state) of the structural element. One of the main advantages of strengthening with FRP sheets is the increased ductility that the FRPs can provide. If a RC element is reinforced with external FRP, there is usually great capacity at steel yielding. By using FRPs to retrofit RC elements the capacity can be increased as high as three times the original strength, depending on the properties of the concrete and the mechanical properties of the FRPs [33–36].

Seismic applications of FRP materials can be important to structural members because there are some important structural deficiencies like low quality concrete; poor confinement of the end regions, weak column-strong beam behaviour, short column behaviour, inadequate lengths and improper hooks of the stirrups. These structural deficiencies usually cannot provide the required ductility, lateral stiffness and strength that structures need to survive earthquakes [37].

Over the years, several seismic repair and retrofitting techniques like concrete strengthening with FRP sheets have been investigated. The key advantage of this technique is the stiffness and the strength that this composite application provides. However, stiffer beam-column joints would attract more forces during the earthquake. Mosallam tested a total of four full-scale reinforced concrete-tie beam assemblies, Figure 2-6. These assemblies were tested under sustained axial column load and full lateral reversed cyclic loading conditions.

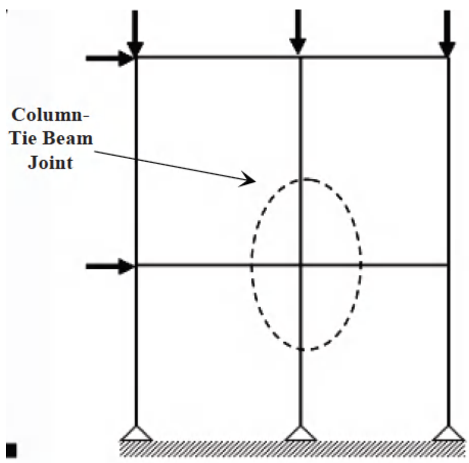

Figure 2-6. Typical column-tie beam joint [37].

The strengthening layup system used was carbon/epoxy and E-glass/epoxy. The experimental results showed that by using the two FRP composite systems the strength, stiffness and ductility of the RC column-tie beam joint was enhanced. As compared to the un-strengthened joint specimen, the strength increased in the strengthened specimens up to 152% and 154% for both FRP systems used [38].

2.6 Shear in beams

The main subject of this thesis is flexure and shear strengthening of RC beams. Because of the complicated nature of the shear behaviour a general discussion of the behaviour, the mechanisms and failure modes of concrete beams under shear load is presented in this chapter.

2.6.1 Mechanism of shear transfer

There are two shear mechanisms that are acting in a beam without stirrups, an overview can be seen in Figure 2-7 [39].

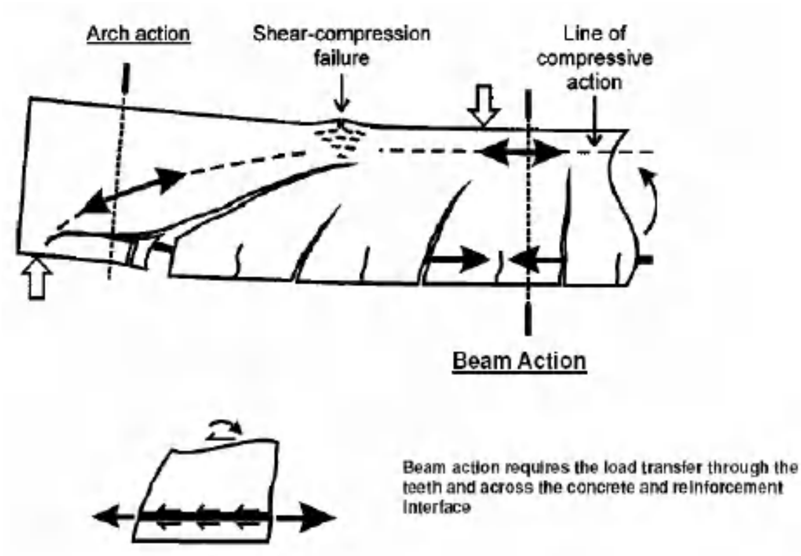

Figure 2-7. Shear in beams without stirrups [38].

The moment carried by the beam is the internal forces between the compression zone and flexural reinforcement. For equilibrium in the shear span the equation 1 here below has to be fulfilled, where the shear force is present wherever the bending moment in the member varies along its length.

$$V = \frac{dM}{dx} \tag{1}$$

Therefore, one of two mechanisms can influence the change in moment:

- Internal actions (Beam action)
- Arch actions

The main problems of the shear behaviour are the parameters involved, the parameters are described here below. Therefore, researchers have been concentrated on the internal actions of shear failure and have tried to determine the contribution from the involvement of the parameters. There are at least three internal actions of shear transfer acting on a beam cross-section, they are illustrated in Figure 2-8.

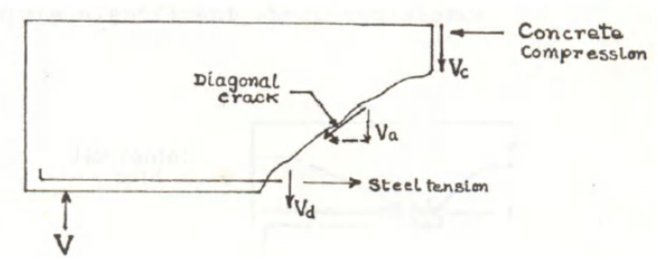

Figure 2-8. Shear transfer mechanisms [39].

The total shear force of a member is based on actions of various forces

$$V = V_c + V_d + F_F \tag{2}$$

where,
V_C is the shear in compression zone with the contribution of 20 to 40%.
V_d is the shear from dowel action with the contribution of 15 to 25%.
V_F is the shear from aggregate interlock with the contribution of 35 to 50% [40].

2.6.2 Internal actions

2.6.2.1 Shear in compression zone (V_C)

While the concrete is un-cracked it carries the shear. After the concrete starts cracking all others internal actions come into play and the shear carried in the compression zone reduces. The concrete usually starts to crack when the aggregate interlock reaches failure [37].

2.6.2.2 Shear with dowel action (V_{dow})

Dowel action is used to describe the shear capacity of a reinforcing bar crossing a cracked plane. Therefore, it is affected by the bending and shear stiffness of the bar. A reduction in bar diameter should lead to a considerable reduction in the contribution of dowel action to shear capacity [41–44]. Figure 2-9 displays how the dowel action splits horizontally along the longitudinal reinforcement [40].

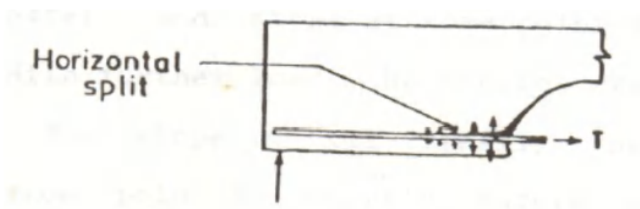

Figure 2-9. Splitting along reinforcement due to dowel action [39].

2.6.2.3 Shear from aggregate interlock (V_F)

The main contributor to shear resistance is aggregate interlock. The most important variables are the aggregate size, width of the crack and the concrete tensile strength. If the longitudinal reinforcement is enhanced the shear resistance is increased in this manner [42–44]. .

2.6.3 Arch actions

Arch action occurs in the un-cracked concrete on the shear-span zone, where load is carried from the compression-zone to the support by a compressive strut. Kani did one of the earliest researches on shear failure in 1964 at University of Toronto Canada [45]. Kani defined the regions of beam action (Internal action) and arch actions for resisting shear in beams. In Figure 2-10 a model that Kani proposed is demonstrated. Values of a/d below 2.5, beams will develop arch action. For a/d values greater than 2.5 and beams will develop beam action [46]. About arch action and beam action, it's when beams develop a flexure-shear interaction, it's when shear force and bending moment act together in a beam cross-section, and the equation here below has to be fulfilled:

$$\frac{a}{d}=\frac{M}{(Vd)} \tag{3}$$

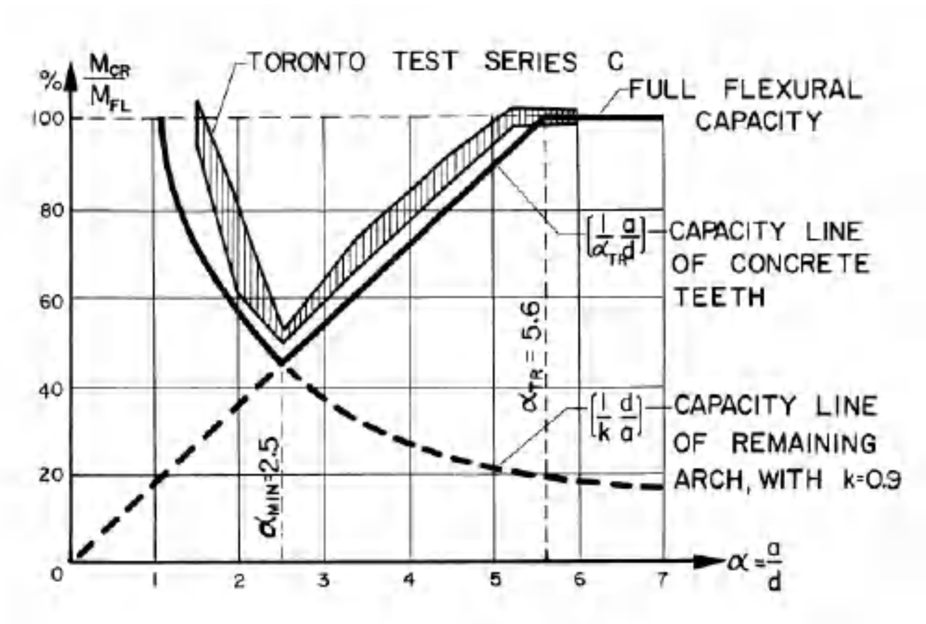

Figure 2-10. Region of arc action and beam action [45].

2.7 Beam shear failure modes

Three distinct modes of shear failure are observed, which describe the manner in which concrete fails:

- Diagonal tension failure
- Shear compression failure
- Shear tension failure

2.7.1 Diagonal tension failure

This type of failure is usually a flexure-shear crack. The diagonal crack starts from the last flexural crack at mid span, where it follows direction of the bond reinforcing steel and the concrete at the support. After that, few more diagonal cracks develop with further load, the tension crack will extend gradually until it reaches its critical point where it will fail without warning. This type of shear failure is always in the shear-span when the a/d ratio is in the range of 2.5 to 6. Such beams fail either in shear or in flexure [36,38-39].

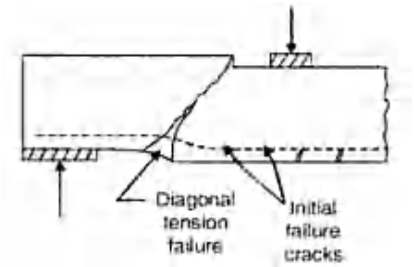

Figure 2-11. Diagonal tension failure [37].

2.7.2 Shear compression failure

This type of failure is common in short beams with a/d ratio between 1 and 2.5. It's called a web shear crack, it's crushing the concrete in the compression zone due to vertical compressive stresses developed in the vicinity of the load [36,39].

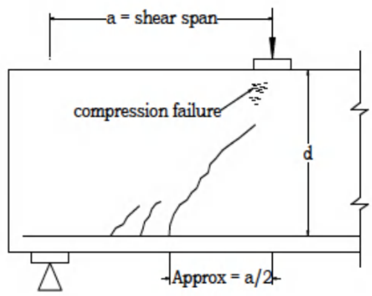

Figure 2-12. Shear compression failure [36].

2.7.3 Shear tension failure

This type of failure is also common in short beams and it is similar to diagonal tension failure. First we can see a shear crack that is similar to the diagonal crack that goes through the beam; the crack extends toward the longitudinal reinforcement and then propagates along the reinforcement that results in the failure of the beam [47].

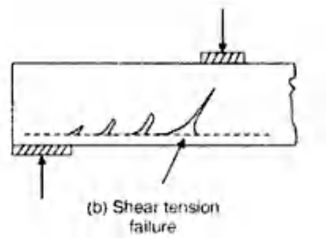

Figure 2-13. Shear tension failure [46].

3 DESIGN GUIDELINES

3.1 Introduction

This chapter provides an introduction to the analytical study concerning the structural behaviour of RC beams strengthened in shear and flexure with externally bonded BFRP reinforcement. Therefore, it will be divided into two design proposals for strengthening of RC structure. In this study two guidelines will be followed, Technical Report No.55 by the Concrete Society; *"Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials"* [16] and American Concrete Institute [21] *"Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures"*.

3.2 American Concrete Institute

The guidelines suggested by ACI Committee 440 on calculations for shear-strengthening effect using FRP shear reinforcement to a reinforced concrete beam or column. The guideline presents guidance on calculations on flexural strengthening effect of adding longitudinal FRP reinforcement to the tension face of a reinforced concrete member. The concepts that are outlined by ACI 440 can be extended to nonrectangular shapes (T-sections and I-sections) and to members with compression steel reinforcement.

3.2.1 Shear strengthening

The nominal shear strength of an FRP-strengthened concrete beam can be determined by adding the shear resistance contribution of the FRP (V_f) to the steel stirrups contribution (V_s) and concrete shear resistance (V_c) according to:

$$V = V_c + V_s + V_f \tag{4}$$

Where V_c and V_s can be determined from design standard, such as ACI 318-08.

The shear contribution of the FRP shear reinforcement can be determined by calculating the force resulting from the tensile stress in the FRP across the assumed crack. Therefore, FRP contribution to shear strength is based on the fibre orientation and the assumed crack pattern [48]. The shear contribution of the FRP shear reinforcement can be determined by:

$$V_f = \frac{A_f E_f \varepsilon_f (\sin\beta + \cos\beta) d}{s_f} \tag{5}$$

where the β is the inclination angle of the FRP, s_f is the width of the FRP, $d=d_f$ is the depth to the shear reinforcement, A_f is the total FRP area that is given by:

$$A_f = 2nt_f s_f \tag{6}$$

where n is the total number of FRP sheets, t_f the thickness of the FRP, E_f is the FRP modulus of elasticity and ε_{fe} is the effective strain that is the maximum strain that can be achieved in the FRP reinforcement system. The maximum strain used for design should be limited to 0.4% for application that is completely wrapped whit FRP.

$$\varepsilon_{fe} = 0.004 \le 0.75\varepsilon_{fu} \tag{7}$$

For U-wrapped or bonded face plies systems the FRP does not close the entire section. Therefore, bond stresses should be analysed to determine the usages and the effective strain level that can be achieved. The effective strain for U-wrapped or face plies can be calculated by using the strain-reduction coefficient K_v:

$$\varepsilon_{fe} = K_v \varepsilon_{fu} \le 0.004 \tag{8}$$

This factor depends on the strengthening scheme, it depends on the concrete strength, type of wrapping scheme used and the stiffness of the sheets. The strain-reduction factor is given by:

$$K_v = \frac{k_1 k_2 L_e}{11900\varepsilon_{fu}} \le 0.75 \tag{9}$$

where the effective length of the FRP sheet is given by:

$$L_e = \frac{23300}{(nt_f E_f)^{0.58}} \tag{10}$$

The remaining factors can be obtained from two modification factors, k_1 and k_2. These two factors depend on the strength of the concrete and the wrapping scheme:

$$k_1 = (\frac{f_c}{27})^{2/3} \tag{11}$$

$$k_2 = \frac{d - L_e}{d} \quad \text{for U-wraps} \tag{12}$$

$$k_2 = \frac{d - 2L_e}{d} \quad \text{for two sides only} \tag{13}$$

3.2.2 Flexure strengthening

In this chapter the flexural capacity of a concrete beam strengthened with BFRP sheet with a cement-based adhesive will be estimated. The same approach is adopted based on the analysis presented in ACI 440 [21]. The geometry that is presented in ACI 440 will be modified to suit the strengthening application with cement-based adhesives.

For concrete members with no compressive reinforcement, the failure modes are not the same as concrete members with compression reinforcement. For concrete members that are without compression reinforcement there are only two modes of failure that exist, failure in the longitudinal BFRP sheets rupture and compression crushing of concrete [49].

In Figure 3-1 the cross section of a concrete member having only tensile reinforcement is shown together with strain development and longitudinal forces. The figure shows the idealized forces, strains and corresponding stresses within a concrete beam that is resisting an applied moment.

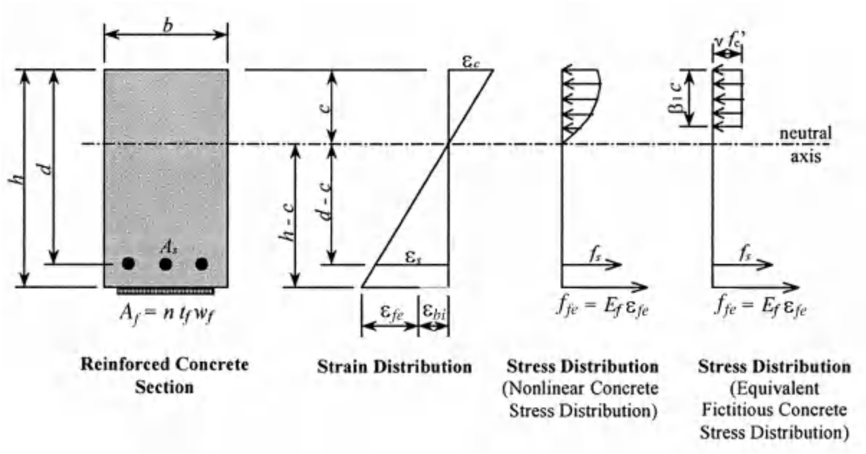

Figure 3-1. Internal stress-strain relationship for tensile reinforced concrete beam with rectangular cross-section [21].

When calculating the flexural capacity of the strengthened section the calculations are based on actual dimensions, internal reinforcement and the material properties of the member that is being strengthened.

First the existing state of strain of the specimen has to be determined. The existing state of strain is assumed to be zero during the installation of the FRP system, because no load was applied to the beam specimens.

$$\varepsilon_{es} = 0 \tag{14}$$

The flexural bond-dependent coefficient of the FRP system has to be determined, by using:

$$\begin{aligned} K_m &= \frac{1}{60\varepsilon_{fe}} - \frac{nE_f t_f}{360000} \leq 0.90 \qquad &\text{For} \quad nE_f t_f \leq 180000 \\ K_m &= \frac{1}{60\varepsilon_{fe}} - \frac{90000}{nE_f t_f} \leq 0.90 \qquad & nE_f t_f > 180000 \end{aligned} \tag{15}$$

The flexural capacity of the strengthened section can be determined by knowing the distance to the actual depth of the neutral axis (x):

$$M = A_s f_s (d - \frac{\beta_1 x}{2}) + A_f E_f \varepsilon_{fe} (h + \frac{t_{CBM}}{2} - \frac{\beta_1 x}{2}) \tag{16}$$

where the A_s and A_f are the area of the steel reinforcement and the FRP reinforcement, f_s is the stress in the steel reinforcement, d is the distance from the compression zone to the tensile reinforcement, β_1 is the ratio of the depth of the rectangular stress block to the depth of the neutral axis, E_f is the tensile modulus of elasticity of the FRP reinforcement, ε_{fe} and ε_f are the effective strain in the FRP reinforcement and the steel reinforcement, h is the overall thickness of the member and the t_{CBM} is the thickness of the FRP cement-based strengthening.

The effective strain in the FRP reinforcement can be determined by:

$$\varepsilon_{fe} = 0.003(\frac{h - x_e}{x_e}) + \varepsilon_{es} \leq K_m \varepsilon_{fu} \tag{17}$$

Where x_e is estimated, x_e=0.20d. The maximum usable compressive strain in the concrete is 0.003.

The actual depth to the neutral axis is determined by internal force equilibrium

$$x = \frac{A_s f_s + A_f E_f \varepsilon_f}{\beta_1 f_c b} \tag{18}$$

The stress level in the steel reinforcement should be calculated: $f_s = E_s\varepsilon_s$, if $f_s \leq f_y$, f_s should be used otherwise f_y.

where the ε_s is the strain in the existing reinforcement, it can be determined by:

$$\varepsilon_s = (\varepsilon_{fe} + \varepsilon_{es})(\frac{d - x}{h - x}) \tag{19}$$

Not that the equivalent rectangular stress block β_1 is taken from ACI 318-08, Section 10.2.7.3 [50], for f_c above 28 MPa, β_1 shall be reduced linearly at a rate of 0.08 for each 7 MPs of strength in excess of 28 MPa, but it shall not be less than 0.65.

3.3 British Concrete Society

The TR55 Report by the British Concrete Society provides a design and construction guidelines on strengthening concrete structures with FRP materials.

These guidelines are set in context of British design codes and standards. The design procedures are applicable to all FRP materials and all strengthening techniques. The procedures are based on generally accepted principles. The Report provides a guideline for strengthening RC members in flexure and in shear. Also this report requires that the ultimate capacity of the existing sections should be assessed by conventional concrete design methods. For the calculations in this chapter the EN 1992-1-1:2004 will be used [51].

3.3.1 Shear strengthening

The ultimate shear capacity for a beam strengthened with FRP can be determined by adding the contribution from the concrete (V_c) to the contribution from the FRP (V_f) and the steel stirrups contribution (V_s), therefore it can be expressed as:

$$V = V_c + V_s + V_f \tag{20}$$

Where V_c and V_s can be determined from design standards, such as EN 1992-1-1:1994.
The contribution of the FRP reinforcement can be determined by the equation that is expressed as:

$$V_f = E_f \varepsilon_{fe} A_f \frac{(d - \frac{n}{3} l_{t,\max})}{s_f} (\cos\beta + \sin\beta) \tag{21}$$

Where E_f is the tensile modulus of elasticity of the FRP reinforcement, ε_{fe} is the effective strain in the FRP reinforcement, A_f is the area of the FRP reinforcement, d is the effective depth of the FRP reinforcement measured from the compression zone of the member to the tensile reinforcement, n is 0 for a fully wrapped beam, 1.0 for U-wrapped and 2.0 when it is bonded to the sides, $l_{t,max}$ is the anchorage length required to develop full anchorage capacity, $l_{t,max} = 0.7\sqrt{(E_f\, t_f/f_{ctm})}$, s_f is the longitudinal spacing of the FRP sheets used for strengthening, it is taken as 1.0 for continuous FRP sheet, β is the angel between the principal fibres of the FRP and a line perpendicular to the longitudinal axis of the member.
The effective strain in the FRP reinforcement should be taken as the minimum of $\varepsilon_{fd}/2$, $0.64\sqrt{(f_{ctm}/E_f\, t_f)}$ or 0.004, where the f_{ctm} is the tensile strength of the concrete and ε_{fd} is the design ultimate strain capacity of the FRP reinforcement.

3.3.2 Flexural strengthening

The procedures for calculating the nominal strength of beam are summarized as follows.

The maximum allowable strain in the FRP reinforcement has to be determined to find the neutral axis of the strengthened section. The Concrete Society committee recommends that when FRP reinforcement is used in relation with a limit on maximum shear stress between the FRP and the concrete, the strain in the FRP reinforcement (ε_f) should not exceed 0.8%. Therefore, the neutral axis can be given by:

$$0.85 f_c bx = f_s A_s + E_f A_f \varepsilon_f \qquad (22)$$

It is important to calculate the strain in the concrete and the reinforcement steel. The equation here above is not valid if the concrete crushes and the steel doesn't yield when the ε_s = 0.008.

$$\varepsilon_c = \frac{x}{h-x}\varepsilon_f < 0.0035 \qquad (23)$$

$$f_s = E_s(\varepsilon_f \frac{d-x}{h-x}) < f_y \qquad (24)$$

The stress level in the steel reinforcement should be calculated: $f_s = E_s\varepsilon_s$, if $f_s \le f_y$, f_s should be used otherwise f_y.

The design flexural strength of the section is calculated by taking moment about the bottom face, the moment is given by:

$$M = 0.85 f_c bx(z + (h + \frac{t_{CBM}}{2} - d)) - f_s A_s (h + \frac{t_{CBM}}{2} - d) \qquad (25)$$

where

$$z = d - 0.9\frac{x}{2} \qquad (26)$$

4 EXPERIMENTAL WORK

4.1 Introduction

This chapter reports the experimental program of the research that was conducted. The experimental work will be described in following sections: Section 4.2 provides a description of the experimental work and the material properties of the beam specimens. Section 4.3 describes the experimental study that was done on the cement-based material that was used to strengthen the beams. Section 4.4 describes the experimental work on BFRP material, where an tensile test was made to find the material properties of the BFRP and the epoxy resin used. Details of the specimens, test set-up and the properties of the materials used are presented in this chapter. The results from these experiments are discussed in chapter 5.

4.2 Beam test specimens

4.2.1 Description of beam specimens

The test specimens were comprised of 22 RC beams of rectangular cross-section. The beams were casted in three groups, see Table 6. These groups were:
Group a. Comprised of eight beams (BS1-BS8), two of which were reference specimens and the others were strengthened for shear with BFRP, using epoxy adhesive.
Group b. Comprised of six beams (BS1-BS6), three of which were reference beams, while the others were strengthened for shear with BFRP, using epoxy adhesive.
Group c. Comprised of eight beams (BF1-BF8), two of which were reference beams, while the others were strengthened for flexure with cement-based material as bonding material for the BFRP.

All beams had the width of 150 mm, total depth of 250 mm and a span length of 2.5 m and total length of 3 m. The dimensions of the beams for all the groups are shown in Figure 4-1 and Figure 4-2. The beams in groups a and b were designed in such a way to ensure that all beams would fail in shear. Therefore, no internal shear reinforcement was provided within the interior shear span. Extremes of dimensional and reinforcing were considered following section 5.4.2.1 of ACI 125 [21].

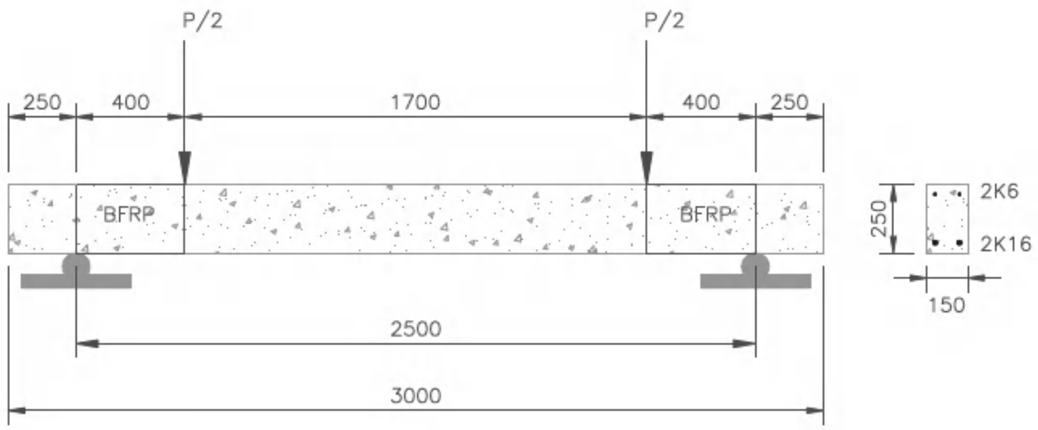

Figure 4-1. Beams in group a and b. Strengthened for shear with epoxy as an adhesive.

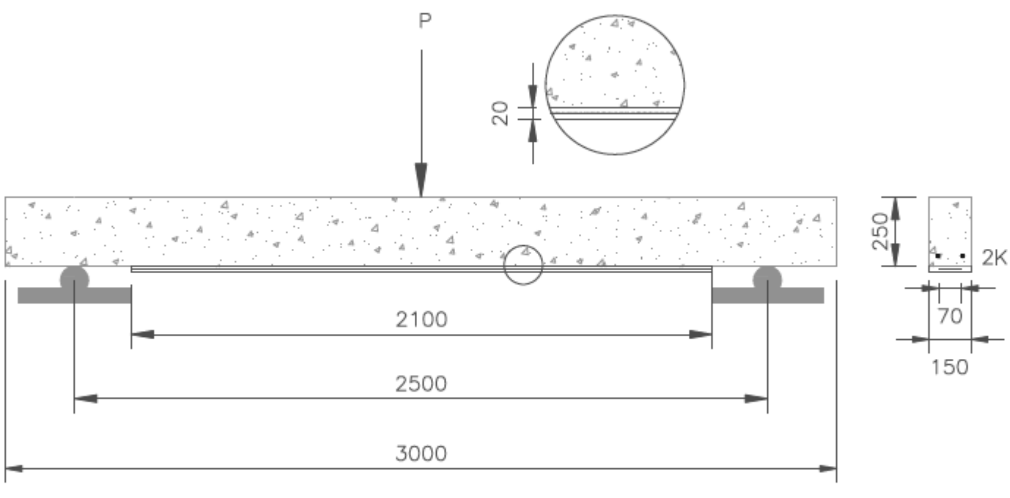

Figure 4-2. Beams in group c. Strengthened for flexure with cement-based material as a bonding material.

4.2.2 Material properties

4.2.2.1 Internal reinforcement

S500 steel bars were used as internal reinforcement with a characteristic yield stress of 500 MPa. For groups a and b the longitudinal steel reinforcement was 2Ø16 but 2Ø12 for group c. The beams in groups a and b are characterized by steel reinforcement ratio $\rho_s=A_s/bd$ and FRP reinforcement ratio $\rho_f=A_f/bd$. The test parameters can be seen in Table 6.

Table 6. Parameters of beam test specimens.

Group	Spec.	Strengthening layout	Age at test	Modulus of elasticity	fc	ρs	ρf	Load during strength.
			(day)	(GPa)	(MPa)	(%)	(%)	(kN)
a	BSa1-BSa2	Unstrength. (Ref)	28	27	31	1,3	-	Self weight
	BSa3-BSa4	1 strip (90° U shape)	28	27	31	1,3	0.9	Self weight
	BSa5-BSa6	1 strip (45° U shape)	28	27	31	1.3	0.6	Self weight
	BSa7-BSa8	3 strip (45° U shape)	28	27	31	1.3	1.8	Self weight
b	BSb1-BSb3	Unstrength. (Ref)	28	29	30	1.3	-	Self weight
	BSb4-BSb6	3 strip (45° O shape)	28	29	30	1.3	1.8	Self weight
c	BFc1-BFc2	Unstrength. (Ref)	32	33	56	0.7	-	Self weight
	BFc3-BFc4	1 strip 90° - Acryl	32	33	56	0.7	0.2	Self weight
	BFc5-BFc6	1 strip 90° - Fibre	32	33	56	0.7	0.2	Self weight
	BFc7-BFc8	1 strip 90° - SP	32	33	56	0.7	0.2	Self weight

4.2.2.2 External reinforcement

The external bonded reinforcement consisted of two types of BFRP sheets. First, BAS BI 450 which is a multiaxial fabric where the fibres lay in both directions, 45°. The second type of fibre used is BAS UNI 600 that is unidirectional fabric were the main fibres are in the longitudinal direction. The main properties of dry fibres given by the manufacturer are shown in Table 7. More information can be found in Appendix A1.

Table 7. Material properties given by manufacturer.

Material	Nominal thickness	Surface weight	Ultimate tensile strain	Elastic modulus	Tensile strength
	(mm)	(g/m^2)	(%)	(GPa)	(MPa)
BAS BI 450	0.45	464	3.15	84	2500
BAS UNI 600	0.65	657	3.15	84	2500

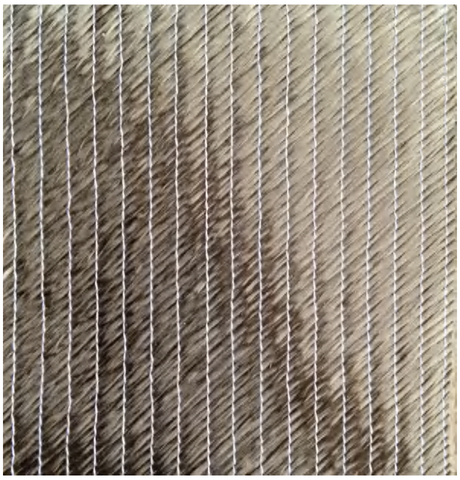

Figure 4-3. BFRP fabric: BAS BI 450.

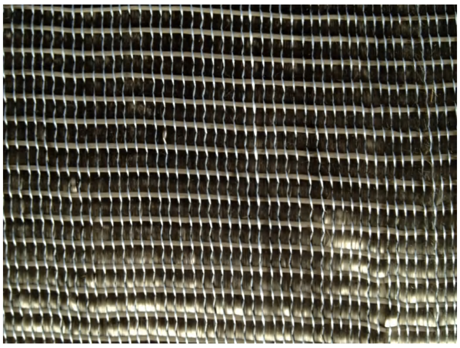

Figure 4-4. BFRP fabric: BAS UNI 600.

4.2.2.3 Concrete

The concrete was supplied by the Ready mix station Steypustöðin which was used for casting all the beams and the casting took place at the ICI Rheocenter Iceland, see Figure 4-10 and Figure 4-11. Measurements were carried out on the fresh concrete such as slump, slump flow, air content and density. The properties of the fresh concrete are displayed in Table 8. Measurements on hardened concrete included the compressive strength according to standard EN 12390-3:2001 [52] as well as the elastic modulus according to ISO 6784 [53]. The compressive strength for each concrete casting was determined on 3x3 standard 100 mm x 200 mm concrete cylinders. The samples were in the moulds for 24 hours, thereafter they were taken from their moulds and stored at 100% relative humidity until testing. The compressive strength was tested after 1, 7 and 28 days, except the specimen for group c were tested at 32 days (due to schedule differences for the equipment).

The compressive strengths at 28 and 32 at days is displayed in Table 6. The 1st and 7th days compressive strengths are given in APPENDIX B.
The concrete cast for groups a and b was C25 concrete. For group c, a Self Compacting Concrete (SCC) was used, categorised as C35. The mix design reported by the supplier as displayed in Table 9.

Table 8. Properties of fresh concrete.

Group	Slump before casting	Slump after casting	Air	Unit weight	w/c
	(mm)	(mm)	(%)	(kg/m^3)	
a	170	165	8.2	2270	0.55
b	160	180	7.9	2273	0.53
c	640	660	6.2	2330	0.41

Table 9. Concrete mix design reported by the supplier.

Group	Concrete	Aalborg cement	Fly ash	Sand	Aggregate	Water	Super plasticizer
		(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/cm^3)	(kg/cm^3)	(kg/cm^3)
a	C25	315	-	844	945	141	3.15
b	C25	315	-	880	909	170	3.15
c	C35 (SCC)	450	120	975	594	177	5.70

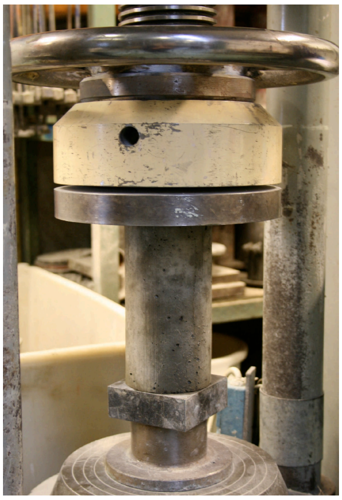

Figure 4-5. Compressive strength testing for cylinders.

Figure 4-6. Slump test, C25.

Figure 4-7. Slump flow test, C35 (SCC).

4.2.3 Specimen preparation

The beams were made using plywood formwork and it was constructed at ICI Rheocenter Iceland, see Figure 4-8. Wire ties were used to keep the longitudinal reinforcement in place. The formwork was removed after 4 days after casting, see Figure 4-11. The beams were stored covered in plastic sheet until the external BFRP reinforcement was applied to the beams at least 5 days before testing, according to the procedures specified in APPENDIX A2. For group a and b the BFRP reinforcement was glued to the concrete specimens externally with epoxy adhesive (Sikadur 330). The epoxy resin was first applied to the concrete surface, the external BFRP reinforcement was then applied to the concrete surface on the epoxies resins coating, the sheet was rolled to squeeze the air that can be entrapped at the epoxy-concrete or epoxy-sheet interface. The beams that were strengthened with epoxy adhesive had to cure for five days at a room temperature before testing, see Figure 4-12 and Figure 4-13. The concrete specimens in group c, which were strengthened in flexure with cement-based material, were cured for 14 days at a room temperature before testing. Additional information about the specimen preparation for beams in group c is offered in section 4.3.3.

Figure 4-8. Formwork ready for casting.

Figure 4-9. Casting of beams specimens.

Figure 4-10. Beams vibrated.

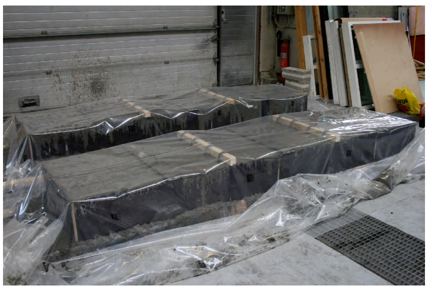

Figure 4-11. Beams wrapped with plastic after casting.

Figure 4-12. BFRP sheet application.

Figure 4-13. BFRP sheet after application.

4.2.4 Test procedure

The beams in groups a and b were tested under 4-point loading, as shown in Figure 4-1 and Figure 4-15. The load was applied by hydraulic jack with a compressive capacity of 500 kN at the ICI Rheocenter Iceland. The testing machine used could not apply the load at a specific load speed. Therefore, the load that was applied was manually controlled at an even rate of speed. During the test the load was recorded from the computer program that the hydraulic jack was connected to. The vertical displacement was also measured but the measurement were not used or presented here. A faulty device measuring the deflection caused the displacements measurements to be incorrect. However, the deflection is of little concern for the research and has limited use.
The position of the applied loads for groups a and b were selected by the shear span-to-depth ratio (a/d=1.9). The shear span-to-depth ratio was selected to satisfy the definition of shear in beams as illustrated in Figure 4-14 [54].
The beams in group c were tested under 3-point loading, as displayed in Figure 4-2. The same test machine was used as for specimens in group a and b. The vertical displacement was measured in the middle, as the difference between the floor and the beam. The failure loads for specimens in all groups and the deflections for the specimens in group c that were recorded will be presented in section 5.1.2.

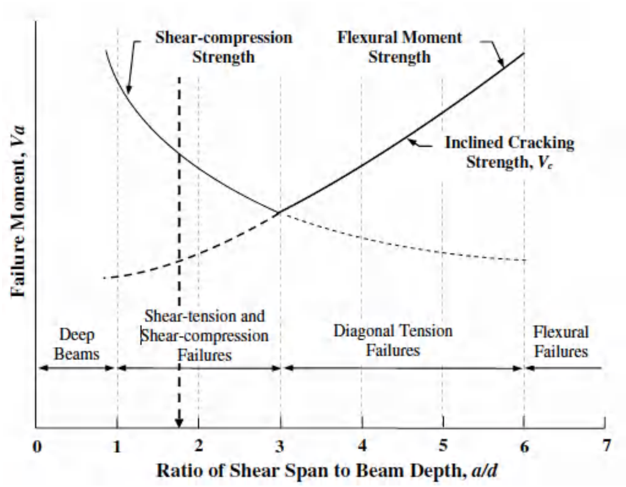

Figure 4-14. Variation of shear failure moment in beams with a/d ratio [53].

Figure 4-15. Four-point load test.

4.3 Cement-based bonding material

4.3.1 Description

In this study, an attempt was made to make High Strength Mortar (HSM) as cement-based bonding material. Eighteen different mix designs were cast and tested as bonding agents. Three of the mixtures with the best mechanical performance were chosen for strengthening BFRP sheets. The dimension of the beam specimens that were strengthened in flexure with cement-based bonding material is shown in Figure 4-2.

4.3.2 Material properties and mixtures

The cement used for the mortar mixtures was CEM I 52.5 N from Aalborg Cement. The aggregates were standardized (EN 196-1) sand from Germany, the maximum size was of 2 mm. One type of Silica Fume (SF) was used, undensified powder from Elkem. Procon SPC 25 (FM) from the producer Omnicon was implemented as the super plasticizer (SP), see APPENDIX A5 for further information. Acryl was also used as an admixture. In Iceland it is used as an admixture in mortar to repair and maintain concrete. Its used can enhance workability, adhesion and the tensile strength, see APPENDIX A4 for further information. Two types of synthetic micro fibres were used, STRUX 90/40 and STRUX BT50. More details on the micro fibres can be seen in Table 10 and in APPENDIX A3.

Table 10. Properties for synthetic micro fibres used.

Material	Specific gravity	Tensile strength (MPa)	Modulus of elasticty (GPa)
STRUX 90/40	0.92	620	9.5
STRUX BT50	0.91	550	7

A total of 18 mixtures were prepared and mixed in the laboratory at the ICI RheoCeneter Iceland. The mixtures were mixed under laboratory conditions at room temperature in the ConTec Rheomixer. Three mixtures were prepared as control specimens. The control mixtures were made of aggregates, cement, water and SP. The other mixtures had different values of SP, SF, micro-fibres and different values of Acryl with and without SP.

It was decided to cast eight small-scale unreinforced concrete beams with normal C25 concrete, test them by strengthening them in flexure with cement-based bonding material. The dimensions of the small-scale beams were 100 x 100 x 360 mm. Eight beams were cast, one of which was a reference beam, one was tested with base and the BFRP sheet was laid in Acryl. The other six specimens had three types of cement-based material that were chosen from the 18 mixtures already done before. The three mixtures chosen are given in Table 11.

Table 11. Mixture proportions for the selected mortars.

Constituents	Mix 1 1.3% SP (kg)	Mix 2 0.75% STRUX BT50 (kg)	Mix 3 11% Acryl (kg)
EN sand	20250	20250	20250
Water	3119	3153.0	3448
Cement	11250	11250	11250
Silica fume	1125	1125	1125
Omnicon	373	314	112.2
Acryl	-	-	380
Fibres-STRUX BT50	-	106	-
sand/cement (s/c)	1.8	1.8	1.8
water/binder (w/b)	0.27	0.27	0.30

4.3.3 Specimen preparation

The mixtures were prepared by first dry mixing the sand and cement in the Rheomixer. The water and the admixtures were added 30 seconds after the dry mixing. The total mixing time was 6.5 minutes. After mixing the cement-based material was put into moulds 100 mm x 40 mm x 40 mm for flexural strength testing. The moulds were covered with plastic and cured for 24 hours. Immediately there after the specimens were de-moulded and cured at 20°C temperature in plastic for 2 days until testing day.

For the full-size specimens the concrete beams were washed by high-pressure water, to remove the weak surface of the concrete. A grinding machine was substrate to the concrete to provide a rough surface, as seen in Figure 4-16. The dimensions for the full-size specimens and the load-setup is displayed in Figure 4-2. The figure displays that only one layer of BFRP sheet was used, first layer of cement-based bonding material was poured followed by the BFRP sheet then came another pour of cement-based bonding material. A frame was built as a formwork on the beam specimens so it would be easier to apply the cement-based material.

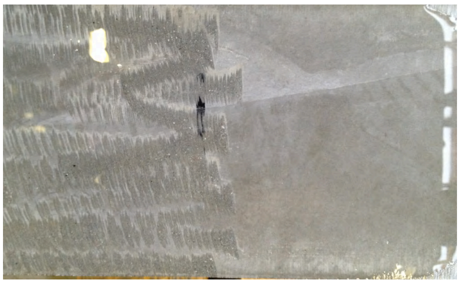

Figure 4-16. Concrete surface.

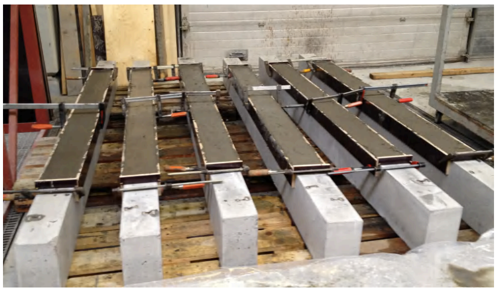

Figure 4-17. The BFRP strengthened system with cement-based adhesive.

4.3.4 Test procedure

Flexural and compressive strength tests were conducted according to EN 196-1:2005 [55] 48 hours after casting. Also a pilot study was carried out where flexural strength test was conducted on the small-scale beam specimens with 10 mm of cement-based bonding material. The main purpose with the small-scale beam specimens was to investigate the bonding and strengthening effect of different mortar used. The results of these tests can be found in section 5.2.1.

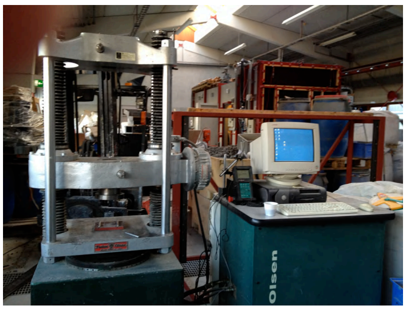

Figure 4-18. TinusOlsen testing machine.

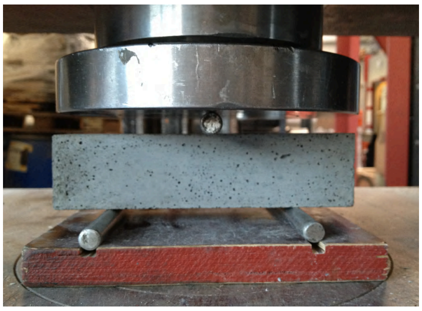

Figure 4-19. Flexural strength test, before testing.

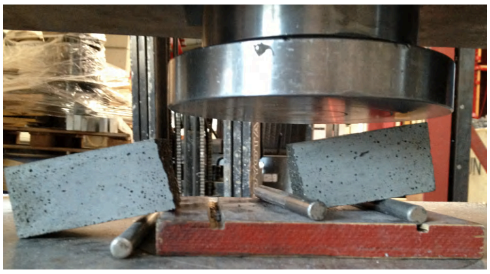

Figure 4-20. Flexural strength test, after testing.

Figure 4-22. Compressive strength test, before testing.

Figure 4-21. Compressive strength test, after testing.

Figure 4-23. Testing cement-based material on small beams.

Figure 4-24. Testing cement-based material on small beams,

Figure 4-25. Flexural testing on small-scale beam specimens.

4.4 Tensile test of BFRP material

4.4.1 Description

The tensile test was carried out in accordance to ASTM D3039 [56]. The tensile test is used to determine both the strength and modulus values in composite materials. It is necessary to find the strength and the modulus of a composite material that is used in the experiment. The manufacturer gives only the properties of the dry fibre, which can be used if a reduction factor is known. The tensile test was performed on two types of BFRP sheets, unidirectional fabric, BAS UNI 600 as well as the multiaxial fabric, BAS BI 450.

4.4.2 Material properties

4.4.2.1 BFRP

Properties for the BFRP material used are given in section 2.4.1.

4.4.2.2 Epoxy resin

Sikadur 330 resin was used as an adhesive. The main properties of the adhesive is the tensile strength of 30 MPa and the elastic modulus of 4.5 GPa. More information about the Sikadur 330 can be found in APPENDIX A2.

4.4.3 Specimen preparation

The dimensions of the specimens were determined in accordance with the ASTM standard, using a minimum of five specimens for a total of 10 specimens. The dimension for the specimen: overall length 250 mm, width of 25 mm and thickness of 0.65-1.95 for BAS UNI 600 and 0.45-1.35 for BAS BI 450, as displayed in Table 12.

Table 12. Number and size of specimens for tensile test.

Material	Numer of specimens	Overall lengt	Width	Thickness
		(mm)	(mm)	(mm)
BAS UNI 600	5	250	25	0.65-1.95
BAS BI 450	5	250	25	0.45-1.35

The BFRP fabric for both materials was cut down to 300 x 150 mm pieces so it would be easier to handle and role. Flat plywood was put on a table and a thin plastic film was applied to it. The pieces of the BFRP material was laid on the plastic film and epoxy resin and was rolled on to it with a paint roller. Any air that may be entrapped was removed using the paint roller. Again, a plastic film was put on the top of the plate to cover it and another plate was put on top for compressing purpose so the specimen would be straight. The plates were left before being cut to exact shape for testing, and were cut by a band saw.
While the specimens were cured, strain gauge was attached to all specimens for measuring the longitudinal strain. According to the standard the strain gauge should be located in the middle of the specimen and its recommended that the strain gauge should have an active strain gage length of 6 mm, it should not be less than 3 mm. A 6 mm strain gauge was attached at mid-section on the BFRP on each side of the specimen, test specimens are displayed in Figure 4-26.

Figure 4-26. Tensile test specimens.

4.4.4 Test procedure

The tensile test was performed in a testing machine Tinus Olsen at the Innovation Center Iceland. It was tested under tensile load, at a head displacement rate of 2 mm/min according to ASTM standard. The longitudinal strain was measured simultaneously using two strain gauges on each side of the specimen. Specimens were fixed in jaws, the gripping of the specimen is important to prevent slippage. Here, it was taken as 60 mm. The tensile strength and the modulus of elasticity was determined by adopting the measured value of the BFRP fabric thickness. For the data reading, two computers were used, one for load reading and one for strain reading.

5 EXPERIMENTAL RESULTS

5.1 Beam test

5.1.1 Beams in groups a and b

The test results for beams in groups a and b, in terms of ultimate load, failure modes, and strength increase are given in Table 13 and Table 14.

Depending on the external BFRP shear reinforcement, strength increases is between 20% and 60%. All beams failed in shear by means of diagonal tension. This type of shear failure is characterized by large diagonal shear crack were the crack develops with further load. It extends gradually until it reaches its critical point where it finally fails without a warning.

For the beams in both groups, flexural cracks were observed in the control specimens near the mid-span at the bottom of the beam, at a load level of about 70 kN. The shear cracks began to appear at a load of approximately 80-90 kN. As the load increased, the shear crack developed further up to the critical failure of the beam. As explained in chapter 2.6, shear failure modes are extremely hard to predict. The failure progress of the reference beams observes that beams in both groups have not the same values of ultimate shear load. As displayed in Figure 5-1 to Figure 5-17 that the crack pattern differs between beams; it is similar for the specimens that have low value of ultimate shear load. But when the ultimate shear load increases the patterns are similar but still differ a lot from the beams with lower ultimate shear load.

For the strengthened specimens, it was not possible to observe cracks on the sides of the beam because of the externally bonded BFRP sheets. However, it was interesting that during loading a sound emitted from the beams. The sound increased as the beam reaches its critical point. Other than this sound, there were no warning signals until the specimen suddenly failed. For beams in group a the governing failure mode was de-bonding of the BFRP sheet from the sides of the specimen. While the shear crack opens along the depth of the beam, the tension induces in the BFRP sheet. The resistance forces in the sheets tends to decrease the crack width, by helping the crack to take up more load. For beam specimen number BSa6, it can be assumed that more energy is consumed by the cross-section as seen in number of cracks the beam and how overly cracked the beam is, see Figure 5-8. For beams in group b, the governing failure was due to bonding failure for BSb4 and BSb5 and due to rupture of the BFRP sheet in BSb6.

Table 13. Test results at ultimate load of RC beams in group a.

Specimen:	Strengthening Lay-out	Failure mode	Shear capcity of concrete V_u (kN)	Average shear capcity of concrete (kN)	V_u/V_{ref} (-)
BSa1	Unstrength. (Ref.)	S (DT)	117.0	148.5	1.00
BSa2	Unstrength. (Ref.)	S (DT/CC)	180.0		
BSa3	1 strip (90° U shape)	S (DT/BF)	162.0	176.0	1.19
BSa4	1 strip (90° U shape)	S (DT/BF)	190.0		
BSa5	1 strip (45° U shape)	S (DT/BF)	164.0	193.0	1.30
BSa6	1 strip (45° U shape)	S (DT/BF/CC)	222.0		
BSa7	3 strips (45° U shape)	S (DT/BF)	216.0	215.5	1.45
BSa8	3 strips (45° U shape)	S (DT/BF)	215.0		

S: Shear failure, F: flexural failure

DT: Diagonal Tension failure, BF: Bond failure

CC: Crushing of concrete at the loading point

Table 14. Test results at ultimate load of RC beams in group b.

Specimen:	Strengthening Lay-out	Failure mode	Shear capcity of concrete V_u (kN)	Average shear capcity of concrete (kN)	V_u/V_{ref} (-)
BSb1	Unstrength. (Ref.)	S (DT)	118.0		
BSb2	Unstrength. (Ref.)	S (DT)	105.0	136.3	1.00
BSb3	Unstrength. (Ref.)	S (DT/CC)	186.0		
BSb4	3 strips (45° 0 shape)	S (DT)	223.5		
BSb5	3 strips (45° 0 shape)	S (DT/BF/CC)	228.0	218.6	1.60
BSb6	3 strips (45° 0 shape)	S (DT/BF/CC)	204.3		

S: Shear failure, F: flexural failure

DT: Diagonal Tension failure, BF: Bond failure

CC: Crushing of concrete at the loading point

Figure 5-1. Crack pattern for BSa1 at ultimate load.

Figure 5-2. Crack pattern for BSa2 at ultimate load.

Figure 5-3. Bond failure, BSa3.

Figure 5-4. Crack pattern for BSa3 at ultimate load.

Figure 5-6. Bond failure, BSa4.

Figure 5-5. Crack pattern for BSa4 at ultimate load.

Figure 5-7. Crack pattern for BSa5 at ultimate load.

Figure 5-8. Crack pattern for BSa6 at ultimate load.

Figure 5-9. Crack pattern for BSa7 at ultimate load.

Figure 5-10. Crack pattern for BSa8 at ultimate load.

Figure 5-11. Crack pattern for BSb2 at ultimate load.

Figure 5-12. Crack pattern for BSb2 at ultimate load.

Figure 5-13. Crack pattern for BSb3 at ultimate load.

Figure 5-14. Crack pattern for BSb4 at ultimate load.

Figure 5-15. Crack pattern for BSb5 at ultimate load.

Figure 5-16. Rupture of BFRP sheet on BSb6.

Figure 5-17. Crack pattern of BSb6 at ultimate load.

5.1.2 Test results for beams in group c

The test results for beams in group c, in terms of ultimate load, failure mode, strength increase and ultimate deflection at mid-span are given in Table 15. Throughout the test it was clear that reinforcement action was achieved by using different types of cement-based bonding material for FRP sheet. Depending on the flexural reinforcement, strength increased between 2% and 8% with one layer of BFRP.

All un-strengthened specimens failed in flexure after yielding of steel. Flexural cracks were observed experimentally near mid-span at the bottom of the beam, at a load level of 20 kN. As the load increased, the flexural crack developed further up to the final failure. As displayed in Figure 5-18 is that the load-deflection response is similar for all specimens.

For the specimens that were strengthened, failure was due to rupture of the longitudinal BFRP sheet. The load transfer and the composite action were very high as seen displayed in Figure 5-21. As displayed in Figure 5-18 is that the load-deflection curves look very similar among different strengthening systems used. The beams reach the cracking load and after that the strengthening system becomes active, thereafter the BFRP sheet starts to rupture, Figure 5-22. This behaviour proceeds up to failure. Slippage was evident between the BFRP sheet and the CBM system used. For specimens that contained Acryl in the mix, de-bonding was the main problem. By turning the beams over the strengthened system was loose on the ends. BFc1 (AK1), the strengthened system fell of the beam, for BFc2 (AK2) the strengthened system was pretty loose on one of the ends, however the beam was tested. The beam that was used for AK1 (BFc1) strengthening system, was used again by using epoxy as an adhesive. However, it was interesting during loading a sound emitted from the beam, the sound increased as the beam reaches failure. Other than this sound, there was no warning signals until bonding failure happened. By using epoxy as an adhesive the strength increases about 11%.

The ultimate deflection at mid-span γ_u of the beams is given in Table 15. Compared to the un-strengthened reference beams, the beams strengthened in flexure have smaller mid-span deflection.

Table 15. Test results at ultimate load of RC beams in group c.

Spec:	Strengthening Lay-out	Failure mode	Load capcity of concrete Q_u (kN)	Average load capcity of concrete (kN)	Q_u/Q_{ref} (-)	Max deflection y_u (mm)	Average deflection of beam (mm)	y_u/y_{ref}
BFc1	Unstrength. (Ref.)	F (YS)	49.9	49.2	1.00	21.1	22.2	1.00
BFc2	Unstrength. (Ref.)	F (YS)	48.5			23.3		
BFc3	AK1	BF	-	50.1	1.02	-	17.9	0.81
BFc4	AK2	F (BF)	50.1			17.9		
BFc5	Fibre1	F (YS)	53.8	53.1	1.08	20.5	19.5	0.88
BFc6	Fibre2	F (YS)	52.3			18.4		
BFc7	SP1	F (YS)	53.0	52.2	1.06	19.8	18.4	0.83
BFc8	SP2	F (YS)	51.4			17		
BFc9	EPOXY1	F (BF/YS)	54.4	54.4	1.11	19.4	19.4	0.87

F: flexural failure

BF: Bond failure, YS: Yielding of the steel

CC: Crushing of concrete at the loading point

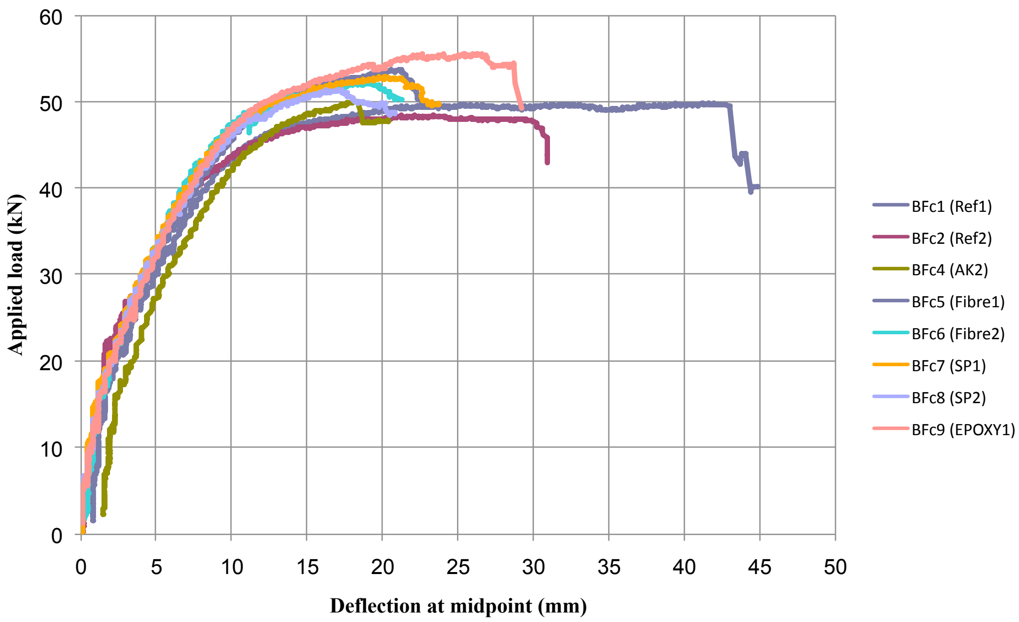

Figure 5-18. Load-deflection relationship for beams strengthened with cement-based bonding material.

Figure 5-19. BFc3 (AK1), Bonding failure before testing.

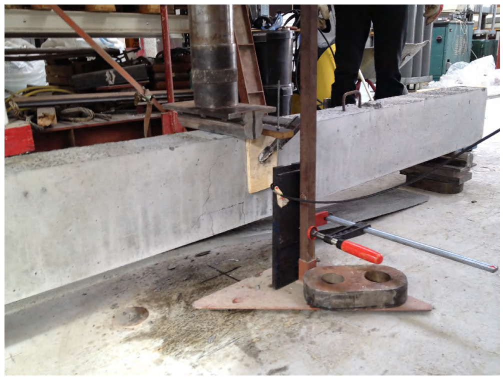

Figure 5-20. BFc4 (AK2), bonding failure during testing.

Figure 5-21. Crack pattern for BFc5 (Fibre1), fully composite action between concrete and CBM.

Figure 5-22. BFc5 (Fibre1), The fibres in BFRP sheet rupture.

Figure 5-23. Crack pattern for BFc6 (Fibre2).

Figure 5-24. Crack pattern for BFc8 (SP2), similar to BFc7 (SP1).

Figure 5-25. Crack pattern for BFc9 (EPOXY1), de-bonding failure.

Figure 5-26. BFc9 (EPOXY1), de-bonding of BFRP.

5.2 Cement-based bonding material tests

5.2.1 Test results from CBM testing

The results from the flexural strength testing for all the mixtures done are displayed in Figure 5-27. Also the test results from the compression testing can be found in APPENDIX D.

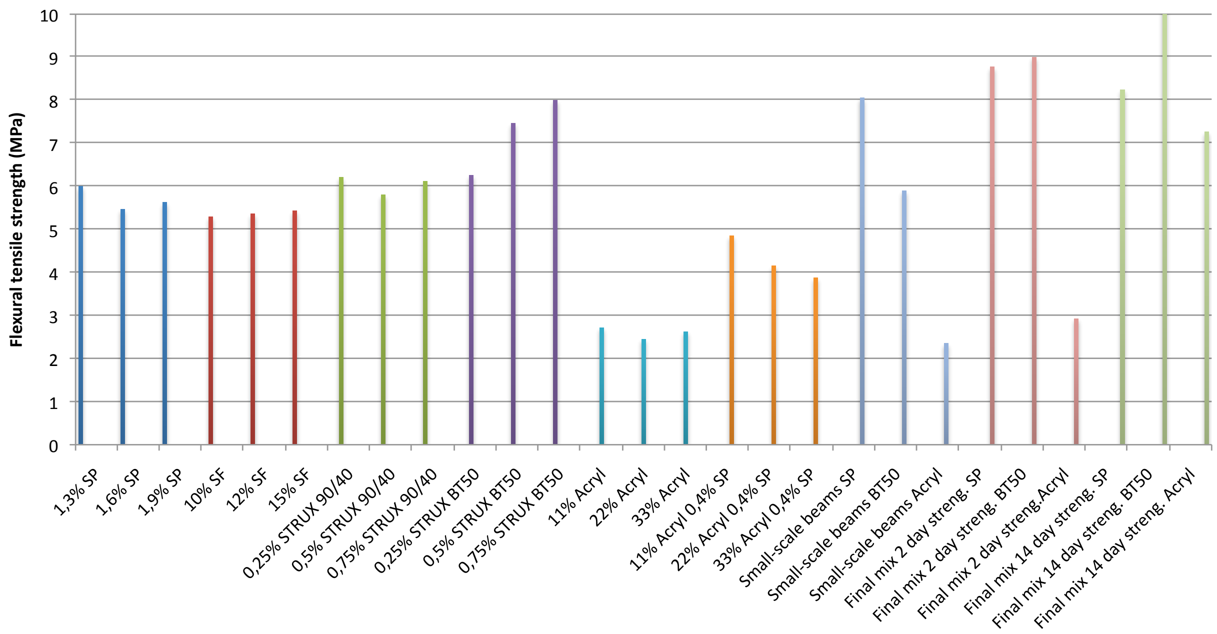

Figure 5-27. Test results for CBM testing

The compressive strength of cement-based bonding material is sometimes used as a principal criterion for selecting the right type of mixture. In this certain experiment the tensile strength (measured in flexure) is more important because it measures the ability of cement-based bonding material to resist cracking. Therefore, by selecting three cement-based material types out of 18 experiments, three of which with the highest flexural strength were selected.

5.2.2 Test results from small-scale beam testing

The test results for the small-scale beams, in terms of ultimate load, failure mode as well as the strength increase is given in Table 16. Throughout the test it was clear that by using cement-based bonding material for FRP sheet, reinforcement action was achieved for FRP sheet. The strength increased way from 26% up to 54% with only one layer of BFRP.

Table 16. Test results at ultimate load for small-scale beams.

Spec:	Strengthening Lay-out	Failure mode	Load capcity of concrete Q_u (kN)	Average load capcity of concrete (kN)	Q_u/Q_{ref} (-)
BF1	Unstrength. (Ref.)	F	11.3	11.3	1.00
BF2	AK+base	F	17.2	17.2	1.52
BF3	SP1	F	14.6	14.3	1.26
BF4	SP2	F	13.9		
BF5	Fibre1	F	17.5	17.5	1.54
BF6	Fibre2	F	17.4		
BF7	AK1	F	16.9	17.4	1.54
BF8	AK2	F	17.8		

F: flexural failure

Figure 5-28. Crack pattern for small-scale beam

5.3 Tensile test for BFRP material

The BFRP material tensile strength is calculated by using the following equation:

$$f_f = \frac{F_{\max}}{A_f} \tag{27}$$

Where F_{max} is the ultimate tensile force before failure, A_f is the average cross-sectional area, which is as following $A_f = n\ t_f\ s_f$ where the n is the number of layers in the specimen, t_f is the nominal thickness of the dry sheet and s_f is the width of the specimen.

The elastic modulus is one of the most important mechanical descriptions of the material. According to the ASTM standard the elastic modulus is calculated within the given strain range from the tensile stress-strain curve as displayed in Figure 5-29. The elastic modulus can be calculated by given the following equation:

$$E_f = \frac{\Delta\sigma_j}{\Delta\varepsilon} \tag{28}$$

Where $\Delta\sigma_j$ is the difference in the applied tensile stress between two strain points, and $\Delta\varepsilon$ is the difference between those two strain points, which is according to the standard 0.1% to 0.3%.

5.3.1 Test results from the tensile testing

From the data measured, stress vs. strain curve was plotted according to the ASTM standard [56], the modulus of elasticity should be calculated between two strain points. All specimens in all groups showed a good linear response between two strain points. In Figure 5-29 the tensile stress vs. strain curve is showed for all five specimens with BAS UNI 600 material. The curves have a good linear response from 0.5% to 1.5%. The elastic modulus for BAS BI 450 material was found with the same procedure as for BAS UNI 600 material.
The ultimate stress and ultimate load was obtained at the failure of specimen and the results are shown in Table 17 and Table 18. In Figure 5-30 the tensile failure is shown for both types of fibres used.

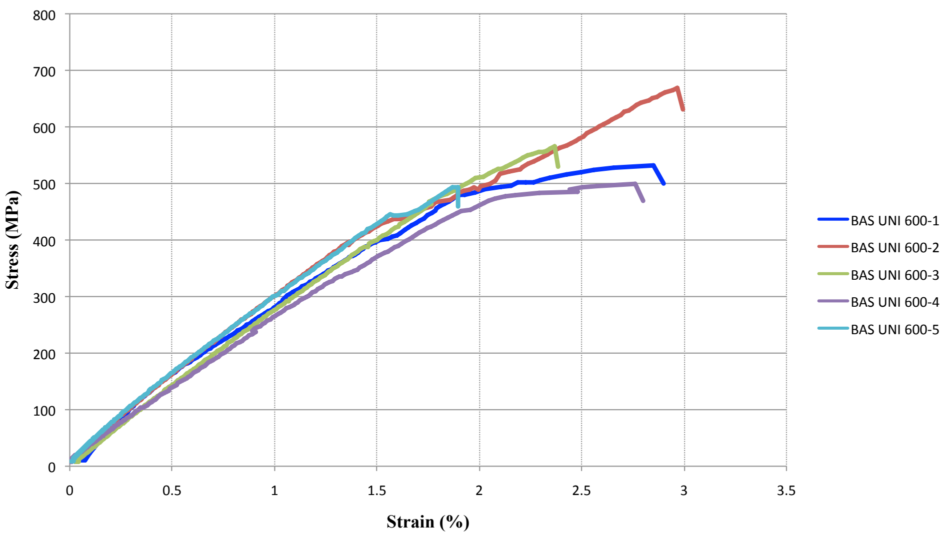

Figure 5-29. Tensile stress vs. strain curve of tensile specimens using BAS UNI 600 material.

Table 17. Results from tensile tests using BAS UNI 600 material.

Specimen	Ultimate load (kN)	Ultimate stress (MPa)	Ultimate Strain (%)	Elastic modulus (GPa)
BAS UNI 600-1	9.5	584.6	2.3	26.8
BAS UNI 600-2	11.1	681.8	2.9	29.4
BAS UNI 600-3	9.3	572.3	2.7	24.8
BAS UNI 600-4	9.5	585.2	2.8	24.5
BAS UNI 600-5	8.4	516.9	2.8	28.3
Average		588.2	2.7	26.8

Table 18. Results from tensile tests using BAS BI 450 material

Specimen	Number of layers	Ultimate load	Ultimate stress	Strain	G
		(kN)	(MPa)	(%)	(GPa)
BAS BI 450-1	1	0.6	52.4	0.9	6.2
BAS BI 450-2	1	0.5	48.8	0.7	9.9
BAS BI 450-3	1	0.6	49.2	0.7	11.9
BAS BI 450-4	1	0.6	53.9	0.8	11.6
BAS BI 450-5	1	0.5	47.0	0.6	10.2
Average			50.3	0.7	10.0
Elastic modulus	E=2G(1+ν)			E =	25.9
ν=0.3					

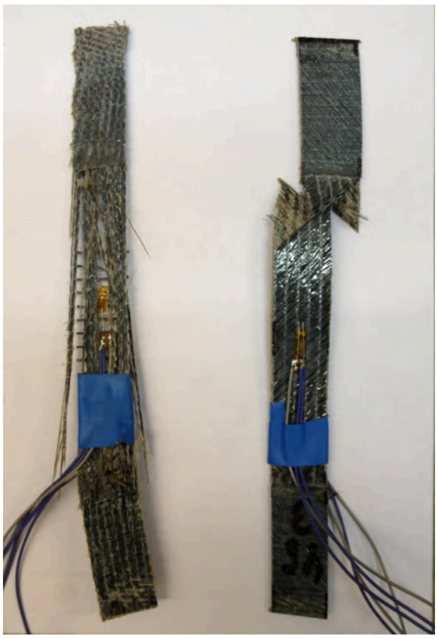

Figure 5-30. Specimen after tensile test.

6 DISCUSSION

6.1 Beam specimens in groups a and b

The major concern in the test results is the difference in the ultimate load capacity for the reference beams. The shear strength of a section highly depends on the failure mode that is controlled by the shear mechanisms as explained in chapter 2.6. In this research, a number of failure modes were observed while doing the experiments. Concrete crushing is assumed to occur when the compressive strain in the concrete reaches its maximum usable strain. Bonding failure can occur if the force in the FRP cannot be sustained by the substrate. Rupture of the FRP sheet is assumed to occur if the strain in the FRP reaches its design rupture strain before concrete reaches its maximum usable strain. To explain the high difference in the ultimate shear load capacity, number of parameters and modes can influence that. The failure load for beam BS2 in group a, is about 52% higher compared to the other reference beams in group a. For beam BS3 in group b is about 70% higher compared to other reference beams in group b. It is obvious in Figure 5-2 and Figure 5-13 that the crack pattern for BS2 in group a and BS3 in group b, that they are similar. As displayed in the figures the angle of the cracks are nearly the same, about 55° explaining that the angle, it will be able to carry more load it can take according to the theory of plasticity [8]. It is hard to predict the test results for beams BSa5 and BSa6, because the results are not significant. The results for BSa5 is similar to BSa4 and BSa6 is similar to BSa7. Therefore, more research is needed to predict the behaviour of the specimens with one layer of 45°.

Shear behaviour and shear strength of RC beams has confused researchers and engineers for many years. Researchers and engineers have been trying to find a rational explanation of the function of the shear mechanism and its effect on the shear capacity of beams. In the experiment that was conducted here the shear mechanism differs, therefore affecting the shear capacity.

It was not fully experimented why there was so much difference in the shear capacity. The things that can influence the shear capacity of the beam, e.g. the distribution of air bubbles in the concrete, air influences the strength of the concrete and depends highly on the vibration. The porosity of the aggregate, unfortunately Icelandic aggregates are very porous, the porosity affects their water absorption and thereby it influences the properties of hardened concrete. Aggregates distribution is also important because of aggregate interlock that is the main contributor to shear resistance. Compression failure was noticeable on the beams that had so high shear load capacity that can be explained by aggregate interlock because the concrete usually starts to crack when the aggregate interlock reaches failure. According to Kanis research in 1964 [45], he defines the regions of internal action and arch action for resisting shear in beams. These two actions develop flexure and shear interaction were shear force and bending moment act together. That can be one of the reasons why the shear load capacity differs. The crack pattern also plays a big role in this matter, for the crack pattern in the beams that had so high shear load capacity, the crack headed straight down at first, therefore reaching the longitudinal reinforcement sooner, there the bending moment starts to act with the shear force. Because of extreme longitudinal reinforcement the shear resistance increases the manner of aggregate interlock. The shear crack is the only contributor to shear resistance, only through aggregate interlock.

6.2 Beam specimens in group c

In all of the specimens, except for the specimen that had Acryl as a bonding material, there was a clear increase in flexural bearing capacity. That was achieved by applying BFRP sheet with different types of cement-based bonding materials.

The mixtures with SP and BT50 fibres did perform better than the mix containing Acryl. The main difference of the mix containing Acryl compared to the others is that the acryl mix generated so much air as well as it was not as adhesive as the others. The volume of the acryl mix was twice as much as the other two mixes, due to the air volume in the mixture.

It was assumed that the failure mode would be the composite action between the cement-based bonding material and the BFRP sheet. The BFRP sheet is so dense that by putting it between two layers of cement-based material it would seem like a sandwich. This was not a problem, there was an excellent composite action between these two materials. To prevent this failure mode it is important to have a cement-based bonding material that has excellent bonding properties and also to consider the position of the sheet, especially when it is so dense.

6.3 Comparison of analytical calculations with experimental results

Calculations can be found in APPENDIX E. All safety factors in the calculations were excluded and set equal to 1.0 for the calculations. This was done to have actual test results according to the standards. Comparison of shear contribution from analytical and experimental study.

6.3.1 Beams in group a and b

Table 19. Comparison of shear contribution from analytical and experimental study.

Group	Guideline / Specimen	Strengthening layout	Shear load V_u (kN)	Shear strength of concrete V_c (kN)	FRP shear strength V_f (kN)	Analytical failure load V_{uu} (kN)	V_u/V_{uu}
	ACI 440			*			
a	BSa1-BSa2	Unstrength. (Ref)	74.3	28.7	-	28.7	2.59
a	BSa3-BSa4	1 strip (90° U shape)	88.0	28.7	28	56.7	1.55
a	BSa5-BSa6	1 strip (45° U shape)	96.5	28.7	26.5	55.2	1.75
a	BSa7-BSa8	3 strip (45° U shape)	107.8	28.7	81.8	110.5	0.98
b	BSb1-BSb3	Unstrength. (Ref)	68.2	28.2	-	28.2	2.42
b	BSb4-BSb6	3 strip (45° O shape)	109.3	28.2	79.9	108.1	1.01
	TR55			**			
a	BSa1-BSa2	Unstrength. (Ref)	74.3	30.3	-	30.3	2.45
a	BSa3-BSa4	1 strip (90° U shape)	88.0	30.3	25.7	56	1.57
a	BSa5-BSa6	1 strip (45° U shape)	96.5	30.3	21.6	51.9	1.86
a	BSa7-BSa8	3 strip (45° U shape)	107.8	30.3	74.1	104.4	1.03
b	BSb1-BSb3	Unstrength. (Ref)	68.2	30.3	-	30.3	2.25
b	BSb4-BSb6	3 strip (45° O shape)	109.3	30.3	79.9	110.2	0.99

* $V_c = 0.17 \sqrt{f_c}\, b\, d$ ACI 318-08

** $V_c = \tau_r\, k(1.2+40\rho_s) b\, d$ EN 1992-1-1:2004

Results from the experimental and analytical study are shown in Table 19. The shear strength of all of the beams is calculated using the analytical procedure presented in section 3 and is compared with the experimental results. It is of interest to mention that when the effective strain is calculated with two design guidelines the threshold of the maximum strain increases, therefore the limit of the maximum strain is considered. For both the ACI 440 and TR55, the design approaches overestimated the effective strain for the U-wrap system. Compared to the experimental values for all wrapped system, the design method provides reasonable accuracy. When calculating the shear contribution using both design standard, the design methods used are the same as for fully wrapped systems (n=0). The shear ratio of V_u/V_{uu} (Experimental failure load / Analytical failure load) varies from 0.98 to 1.86.

Figure 6-1 displays the predicted shear strengths versus the experimental shear strengths of the RC beams both strengthened and un-strengthened. The covariance (COV) of the ratios of the experimental and predicted shear strength values for each method is also give. The predicted results using ACI 440 and TR55 exhibit the same trend for the RC beams that are both strengthened and un-strengthened. Note that the COV values are based on the experimental and predicted values. In a study conducted by Mansour, Dicleli and Zhang in 2004 available test data of 176 RC beams was collected. A comparison of predicted shear strength versus experimental shear strength from six building codes was displayed with the values of COV scattered between 15% up to 22% [57].

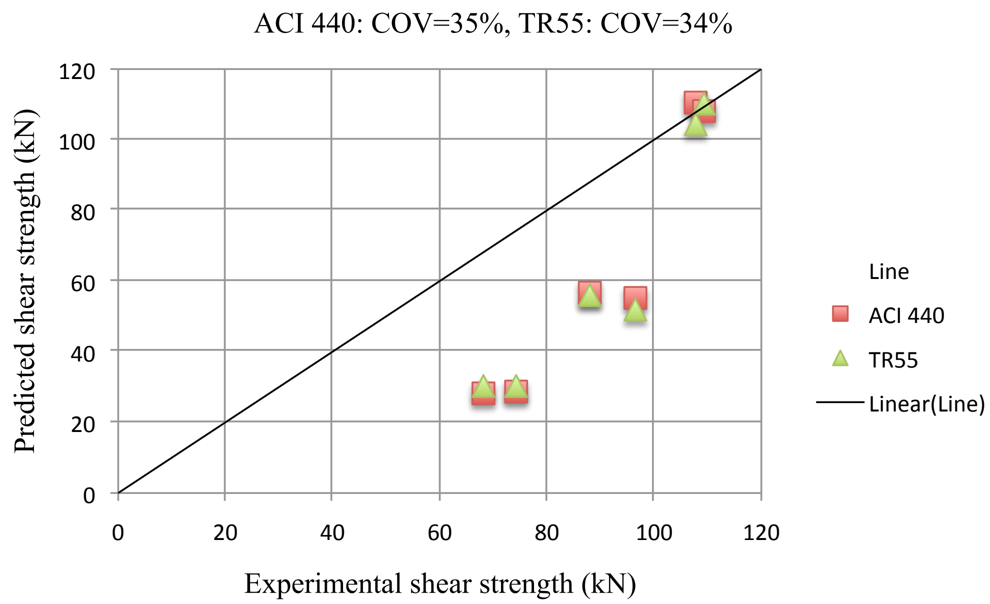

Figure 6-1. Comparison of predicted shear strengths versus experimental shear strengths of the RC beams that are tested.

6.3.2 Beams in group c

Table 20. Comparison of bending moment obtained from analytical and experimental study.

Group	Guideline / Specimen	Strengthening layout	Mean value of Experimental study M_u * (kNm)	Analytical value M_{uu} (kNm)	M_u/M_{uu}
	ACI440				
	BSc1-BSc2	Unstrength. (Ref)	30.8	22.2	1.39
	BSc3-BSc4	AK1	31.3	26.9	1.16
c	BSc5-BSc6	Fibre1	33.2	26.9	1.23
	BSc7-BSc8	SP1	32.8	26.9	1.22
	BSc9	EPOXY1	34.0	26.7	1.27
	TR55				
	BSc1-BSc2	Unstrength. (Ref)	30.8	22.2	1.39
	BSc3-BSc4	AK1	31.3	24.7	1.27
c	BSc5-BSc6	Fibre1	33.2	24.7	1.34
	BSc7-BSc8	SP1	32.8	24.7	1.33
	BSc9	EPOXY1	34.0	24.6	1.38

Results from the experimental and analytical study are shown in Table 20. The comparison between the experimental study to the analytical study is a good estimation for the beams. The ratio of M_u/M_{uu} (Experimental study / Analytical study) varies from 15% to 38%.

7 CONCLUSIONS

In this experimental study the flexural and shear behaviour of RC beams strengthened with externally BFRP sheets were studied. An epoxy adhesive was used to strengthen the RC beams for shear, while cement-based bonding material was used to strengthen beam in flexure.

Shear tests was conducted in two sets using, five reference RC beams and nine RC beams strengthened with BFRP. Flexural testing was conducted in one set using, 2 reference RC beams and 6 RC beams strengthened with BFRP.

From the conducted experimental and analytical study on RC beams strengthened in shear, with externally bonded BFRP reinforcement using epoxy adhesive, the following can concluded:

- By means of externally bonded BFRP shear reinforcement the shear load-carrying capacity of the beams can be increased.
- The shear capacity of the shear strengthened beams were improved by more than 60% by applying the BFRP as externally reinforcement.
- The orientation of the fibres was found to have an important effect, especially where 3 layers were applied in 45° fibre orientation. There was a greater strengthening effect and better control off the shear crack propagations.
- There was inconsistency for the strengthened beams in failure mechanism, in terms of concrete crushing, fibre ruptures or fibres de-bonding.
- Increased efficiency was obtained when BFRP bond failure is avoided or delayed.
- This method, is relatively easy for construction and handling, can be used effectively for strengthening RC beams that require increased shear capacity or confinement.
- The shear strength of concrete beams according to the theory is limited by the many types of failure modes, it does not fully describe the complex behaviour of concrete in shear, although good predictions were seen for the 3 45°stripps strengthening layout.

From the experimental conducted and analytical study on RC beams strengthened in flexure with a cement-based bonding material, the following can be concluded:

- Concrete structures can be strengthened by the use of cement-based bonding material.
- All types of cement-based bonding materials that were used can contribute to increase load carrying capacity of the concrete members.
- Full composite action was obtained between the concrete and cement-based bonding material.
- The strengthened specimens showed an increase in flexural load carrying capacity up to 8% using cement-based bonding material and 11% with an epoxy adhesive.
- Comparing the strengthening effect of the cement-based bonding material system to the epoxy strengthening system using the same size of BFRP sheet, it is clear that the cement-based bonding material provides a similar flexural load capacity.
- The failure of beams strengthened with cement-based bonding material was caused by rupture of the longitudinal fibres.
- For beams strengthened with epoxy adhesive de-bonding of the fibres was the failure.
- The proposed flexural design to estimate the flexural capacity for beams strengthened with cement-based bonding material gave promising results.
- By using Acryl in a mixture does not give good bonding properties because of the air content.

7.1 Limitations

This research is limited to investigate the application of FRP material as external reinforcement. Only simply supported reinforced concrete beams strengthened with unidirectional and multiaxial FRP sheet were studied.

There are some limitations in the flexural design using cement-based bonding material. Firstly, no considerations were taken to the bond-slip behaviour between the concrete base and the strengthening layer. Secondly, a full composite action between the cement-based bonding material and the BFRP sheet was assumed. Long term behaviour and environmental effects were not treated.

7.2 Further research

The author considers that it is hard to accomplish models for FRP strengthening beams in shear until the behaviour of the simple RC beams in shear is solved. In this thesis, several design aspects have been dealt with but not all aspects were covered. It is clear that further research is needed in this field because of the behaviour of RC beams in shear. Factors such as tensile reinforcement, shear span ratio, aggregate size, shape and crack propagation process should be investigated further.

It must be noted that the studied in FRP strengthened with cement-based bonding material is a relatively new subject in this field. Therefore, this topic leads to questions to be answered by means of further research, such as durability.

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APPENDIX A1

BFRP

BASALTEX™
The thread of stone

ISO 9001 A Division of FLOCART nv

Technical Data Sheet
Fabric Type BAS UNI 600

Unidirectional fabric for composite applications, is entirely made of 100% BCF (basalt continuous filament) roving.
The silane sizing is selected, which has components to ensure elasticity of the yarn during textile processes. The sizing allows good compatibility with epoxy, vinyl ester and polyester resin systems.

Property	Standard/Method	Unit	Value	Tolerance
Base material				
Density of unsized filament matl		kg/dm³	2.67	± 5%
Moisture content of basaltic rock		%	0.1	± 0.05
Melting point		°C	1350	± 100
Fabric				
Specific surface weight	ISO 3374:2000	g/m²	657	± 8%
Weave type			UD	
Weight per layer :				
- 0°		g/m²	600	
- 90°		g/m²	50	
- stitching		g/m²	7	
Width**	ISO 5025:1997	mm	1270	± 3%
Thickness	ISO 4603:1993	mm	0.65	
Sizing type			silane	
Moisture content (fabric)	ISO 3344:1997	%	<0.3	
LOI, also sizing content	ISO 1887:1995*	%	0.4 – 0.6	
Combustibility	NF P92-503:1995	M0	Pass	
UV stability	ISO 105-B02		6	
Colour fastness	ISO 1005-BX12		6	

* after drying according ISO 3344:1997

Packaging
Fabric length is approximately 50 lm per roll. Other length on request. Identification label. Standard packing.

Product Stability:
BASALTEX Products have not been designed for full external exposure conditions and cannot be guaranteed for use in such situations. However, these BASALTEX products have considerable tolerance to damp conditions and occasional water immersion. After drying out, the product will give the same level of performance as the original sample.

Stability over time:
Said products not being subjected to excessive heat, wear and abrasion, all evidence obtained to date indicates that their performance should not significantly change over a significant period of time.
It is the responsibility of the developer of the end-product, finished device or system to test its performance in the end-application.

Rev 03.11 BASALTEX Division, FLOCART nv Zuidstraat, 18 B-8560 Wevelgem BELGIUM
PHONE +32(0)56 42 00 95 FAX +32 (0)56 42 42 34 – info.basaltex@flocart.com

BASALTEX™
The thread of stone

ISO 9001 **A Division of FLOCART nv**

Technical Data Sheet
Fabric Type BAS BI 450

Multiaxial fabric for composite applications, is entirely made of 100% BCF (basalt continuous filament) roving.
The silane sizing is selected, which has components to ensure elasticity of the yarn during textile processes. The sizing allows good compatibility with epoxy, vinyl ester and polyester resin systems.

Property	Standard/Method	Unit	Value	Tolerance
Base material				
Density of unsized filament matl		kg/dm³	2.67	± 5%
Moisture content of basaltic rock		%	0.1	± 0.05
Melting point		°C	1350	± 100
Fabric				
Specific surface weight	ISO 3374:2000	g/m²	464	± 8%
Weave type			biaxial	
Weight per layer (Yarn type): - +45° - -45° - stitching		 g/m² g/m² g/m²	 228 228 8	
Width	ISO 5025:1997	mm	1270	± 3%
Thickness	ISO 4603:1993	mm	0.45	
Sizing type			silane	
Moisture content (fabric)	ISO 3344:1997	%	<0.3	
LOI, also sizing content	ISO 1887:1995*	%	0.4 – 0.6	
Combustibility	NF P92-503:1995	M0	Pass	
UV stability	ISO 105-B02		6	
Colour fastness	ISO 1005-BX12		6	

* after drying according ISO 3344:1997

Packaging
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Stability over time:
Said products not being subjected to excessive heat, wear and abrasion, all evidence obtained to date indicates that their performance should not significantly change over a significant period of time.
It is the responsibility of the developer of the end-product, finished device or system to test its performance in the end-application.

Rev 03.11 BASALTEX Division, FLOCART nv Zuidstraat, 18 B-8560 Wevelgem BELGIUM
PHONE +32 (0)56 43 00 95 FAX +32 (0)56 42 42 34 – info.basaltex@flocart.com

APPENDIX A2

Epoxy resin

Product Data Sheet
Edition 0209 / 1
Sikadur®-330

Construction

Sikadur®-330

2-part epoxy impregnation resin

Product Description	Sikadur®-330 is a two part thixotropic epoxy based impregnating resin / adhesive.
Uses	▪ Impregnation resin for SikaWrap® fabric reinforcement for the dry application method ▪ Primer resin for the wet application system ▪ Structural adhesive for bonding Sika® CarboDur® plates to even surfaces
Characteristics / Advantages	▪ Easy mix and application by trowel and impregnation roller ▪ Manufactured for manual saturation methods ▪ Excellent application behaviour to vertical and overhead surfaces ▪ Good adhesion to many substrates ▪ High mechanical properties ▪ No separate primer required
Tests	
Approval / Standards	Conforms to the requirements of: - SOCOTEC (France): Cahier des charges Sika® CarboDur, SikaWrap® - Road and Bridges Research Institute (Poland): IBDIM No AT/2003-04-336 Testing according to EN 1504-4.
Product Data	
Form	
Appearance / Colours	Resin part A: white paste Hardener part B: grey paste Part A+B mixed: light grey paste
Packaging	30 kg (A+B) sets
Storage	
Storage Conditions / Shelf life	24 months from date of production if stored properly in original unopened, sealed and undamaged packaging in dry conditions at temperatures between +5°C and +25°C. Protect from direct sunlight.

Sika®

1 Sikadur®-330 1/6

Technical Data

Chemical Base
Epoxy resin

Density
1.30 kg/ltr ± 0.1 kg/ltr (parts A+B mixed) (at +23°C)

Viscosity
Shear rate: 50 /s

Temperature	Viscosity
+10°C	~ 10'000 mPas
+23°C	~ 6'000 mPas
+35°C	~ 5'000 mPas

Thermal Expansion Coefficient
4.5 x 10^{-5} per °C (-10°C to +40°C)

Thermal Stability
Heat Distortion Temperature (HDT) (ASTM D648)

Curing	Temperature	HDT
7 days	+10°C	+36°C
7 days	+23°C	+47°C
7 days	+35°C	+53°C
7 days, +10°C plus 7 days, +23°C	-	+43°C

Service Temperature
-40°C to +45°C

Mechanical / Physical Properties

Tensile Strength
30 N/mm² (7 days at +23°C) (DIN 53455)

Bond Strength
Concrete fracture (> 4 N/mm²) on sandblasted substrate: > 1 day (EN 24624)

E-Modulus
Flexural:
3800 N/mm² (7 days at +23°C) (DIN 53452)
Tensile:
4500 N/mm² (7 days at +23°C) (DIN 53455)

Elongation at Break
0.9% (7 days at +23°C) (DIN 53455)

Resistance

Chemical Resistance
The product is not suitable for chemical exposure.

Thermal Resistance
Continuous exposure +45°C

System Information

System Structure
Substrate primer - Sikadur®-330.
Impregnating / laminating resin - Sikadur®-330.
Structural strengthening fabric - SikaWrap® type to suit requirements.

Application Details

Consumption
This will be dependant on the roughness of the substrate and the type of SikaWrap® fabric to be impregnated. See respective SikaWrap® fabric Product Data Sheet.

Guide: 0.7 - 1.5 kg/m²

Substrate Quality	The substrate must be sound and of sufficient tensile strength to provide a minimum pull off strength of 1.0 N/mm² or as per the requirements of the design specification. The surface must be dry and free of all contaminants such as oil, grease, coatings, surface treatments, etc. The surface to be bonded must be level (max. deviation 2 mm per 0.3 m length), with steps and formwork marks not greater than 0.5 mm. High spots can be removed by abrasive blasting or grinding. Wrapped corners must be rounded to a minimum radius of 20 mm (depending on the SikaWrap® fabric type) or as per the design specification. This can be achieved by grinding edges or by building up with Sikadur® mortars.
Substrate Preparation	Concrete and masonry substrates must be prepared mechanically using abrasive blast cleaning or grinding equipment, to remove cement laitance, loose and friable material to achieve a profiled open textured surface. Timber substrates must be planed or sanded. All dust, loose and friable material must be completely removed from all surfaces before application of the Sikadur®-330 preferably by brush and industrial vacuum cleaner. Weak concrete/masonry must be removed and surface defects such as honeycombed areas, blowholes and voids must be fully exposed. Repairs to substrate, filling of blowholes/voids and surface levelling must be carried out using Sikadur®-41 or a mixture of Sikadur®-30 and Sikadur®-501 quartz sand (mix ratio 1 : 1 max parts by weight). Bond tests must be carried out to ensure substrate preparation is adequate. Inject cracks wider than 0.25 mm with Sikadur®-52 or other suitable Sikadur® injection resin.

Application Conditions / Limitations

Substrate Temperature	+10°C min. / +35°C max.
Ambient Temperature	+10°C min. / +35°C max.
Substrate Moisture Content	≤ 4% pbw. Test method: Sika-Tramex meter.
Dew Point	Beware of condensation! Substrate temperature during application must be at least +3°C above dew point.

Application Instructions

Mixing	Part A : part B = 4 : 1 by weight When using bulk material the exact mixing ratio must be safeguarded by accurately weighing and dosing each component.
Mixing Time	 Pre-batched units: Mix parts A+B together for at least 3 minutes with a mixing spindle attached to a slow speed electric drill (max. 600 rpm) until the material becomes smooth in consistency and a uniform grey colour. Avoid aeration while mixing. Then, pour the whole mix into a clean container and stir again for approx. 1 more minute at low speed to keep air entrapment at a minimum. Mix only that quantity which can be used within its potlife. Bulk packing, not pre-batched: First, stir each part thoroughly. Add the parts in the correct proportions into a suitable mixing pail and stir correctly using an electric low speed mixer as above for pre-batched units.

Application Method / Tools

Preparation:
Prior to application confirm substrate moisture content, relative humidity and dew point.

Cut the specified SikaWrap® fabric to the desired dimensions.

Resin Application:
Apply the Sikadur®-330 to the prepared substrate using a trowel, roller or brush.

Fabric Placement and Laminating:
Place the SikaWrap® fabric in the required direction onto the Sikadur®-330. Carefully work the fabric into the resin with the Sika plastic impregnation roller parallel to the fiber direction until the resin is squeezed out between and through the fiber strands and distributed evenly over the whole fabric surface. Avoid excessive force when laminating to prevent folding or creasing of the SikaWrap® fabric.

Additional Fabric Layers:
For additional layers of SikaWrap® fabric, apply Sikadur®-330 to previous applied layer wet on wet within 60 minutes (at +23°C) after application of the previous layer and repeat laminating procedure.

If it is not possible to apply within 60 minutes, a waiting time of at least 12 hours must be observed before application of next layer.

Overlays:
If a cementitious overlay is to be applied over SikaWrap® fabric an additional Sikadur-330 resin layer must be applied over final layer at a max. 0.5 kg/m². Broadcast with quartz sand while wet which will serve as a key for the overlay.

If a coloured coating is to be applied the wet Sikadur®-330 surface can be smoothed with a brush.

Overlaps

Fiber Direction:

- Overlapping of the SikaWrap® fabric must be at least 100 mm (depending on the SikaWrap® fabric type) or as specified in the strengthening design.

Side by Side:

- Unidirectional fabrics: when placing several unidirectional SikaWrap® fabrics side by side no overlapping is required unless specified in the strengthening design.
- Multi-directional fabrics: overlapping in the weft direction must be at least 100 mm (depending on the SikaWrap fabric type) or as specified in the strengthening design.

Cleaning of Tools

Clean all equipment immediately with Sika® Colma Cleaner. Cured material can only be mechanically removed.

Potlife

Potlife:

Temperature	Time
+10°C	90 minutes (5 kg)
+35°C	30 minutes (5 kg)

Potlife starts with the mixing of both parts (resin and hardener). At low ambient temperature pot life will be extended, at elevated temperatures this will be reduced. The higher the quantity of material mixed, the shorter the potlife. To achieve a longer potlife at high temperatures the mixed material may be divided into smaller units or both parts may be cooled before mixing.

Open time:

Temperature	Time
+10°C	60 minutes
+35°C	30 minutes

Waiting Time / Overcoating

To (pre-) cured resin:

Products	Substrate temperature	Minimum	Maximum
Sikadur®-330 Sikadur®-330	+10°C	24 hours	Cured resin older than 7 days has to be degreased with Sika® Colma Cleaner and gently grinded with a sandpaper before coating.
	+23°C	12 hours	
	+35°C	6 hours	

Products	Substrate temperature	Minimum	Maximum
Sikadur®-330 Sikagard®-coloured coatings	+10°C	5 days	Cured resin older than 7 days has to be degreased with Sika® Colma Cleaner and gently grinded with a sandpaper before coating.
	+23°C	3 days	
	+35°C	1 day	

Times are approximate and will be affected by changing ambient conditions.

Notes on Application / Limitations

This product may only be used by experienced professionals.

The Sikadur®-330 must be protected from rain for at least 24 hours after application.

Ensure placement of fabric and laminating with roller takes place within open time.

The SikaWrap® fabric must be coated with a cementitious overlay or coating for aesthetic and/or protective purposes. Selection will be dependent on exposure requirements. For basic UV protection use Sikagard®-550W Elastic, Sikagard® ElastoColor-675W or Sikagard®-680S.

At low temperatures and / or high relative humidity, a tacky residue (blush) may form on the surface of the cured Sikadur-330 epoxy. If an additional layer of fabric, or a coating is to be applied onto the cured epoxy, this residue must first be removed to ensure adequate bond. The residue can be removed with water. In both cases, the surface must be wiped dry prior to application of the next layer or coating.

For application in cold or hot conditions, pre-condition material for 24 hours in temperature controlled storage facilities to improve mixing, application and pot life limits.

The number of additional fabric layers applied wet on wet must be closely controlled to avoid creeping, creasing or slippage of the fabric during curing of the Sikadur®-330. The number of layers will be dependent on the type of SikaWrap® fabric used and the ambient climate conditions.

Construction

Curing Details

Applied Product ready for use

Temperature	Full cure
+10°C	7 days
+23°C	5 days
+35°C	2 days

All cure times are approximate and will be affected by changing ambient conditions.

Value Base

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

Sika Kimia Sdn Bhd
Lot 689 Nilai Industrial Estate
71800 Nilai, Negeri Sembilan DK
MALAYSIA

Phone: +606-7991762
Fax: +606-7991980
e-mail: info@my.sika.com
www.sika.com.my

APPENDIX A3

Synthetic micro fibres

Grace Concrete Products

GRACE

STRUX® 90/40

Synthetic macro fiber reinforcement

ASTM C1116

Product Description

STRUX® 90/40 synthetic macro fiber reinforcement is a unique form of high strength, high modulus synthetic macro reinforcement that is evenly distributed throughout the concrete matrix. STRUX 90/40 adds toughness, impact and fatigue resistance to concrete. Unlike traditional microfiber reinforcement, STRUX 90/40 is specifically engineered to provide high, post-crack control performance. Reinforced concrete with STRUX 90/40 has been shown to reliably achieve average residual strength values in excess of 150 psi (1.0 MPa) at dosages that can easily be batched and finished. It consists of synthetic macro fibers 1.55 in. (40 mm) in length with an aspect ratio of 90 that have specifically been designed to replace welded wire fabric, steel fibers, light rebar and other secondary reinforcement in slab-on-ground flooring, thin-walled precast applications and composite steel floor deck. STRUX 90/40 is a user-friendly fiber reinforcement which is easier and safer to use, compared to these other types of reinforcement.

Uses

Slab-on-Ground

STRUX 90/40 is specially designed for ease of use, rapid dispersion, good finishability and improved pumpability in slab-on-ground flooring and many precast applications. STRUX 90/40 may be used in commercial floors, industrial floors, residential floors, other flat work applications and form work applications. The addition rate of STRUX 90/40 can be easily calculated using Grace's SDS Software, using several factors such as compressive strength of concrete, modulus of sub-grade reaction, thickness of concrete and applied load. Please consult your Grace sales representative for proper addition rate of STRUX 90/40 for your application. Always consult local building codes (refer to Engineering Bulletin 1).

Composite Steel Floor Deck for Normal and Lightweight Concrete

STRUX 90/40 can be used as a suitable alternative to WWF specified for temperature and shrinkage reinforcement for composite steel floor decks. STRUX 90/40 complies with *American National Standards Institute/Steel Deck Institute* (ANSI/SDI C-1.0) design code provision for minimum reinforcing at minimum addition rate of 4 lbs/yd^3 (2.4 kg/m^3). STRUX 90/40 is UL (U.S.) and ULC (Canada) classified with fire ratings up to 2 hours for D700, F700, D800, F800, D900 and F900 except 909 at a maximum addition rate of 5 lbs/yd^3 (3.0 kg/m^3).

Product Advantages

- Savings from lower labor costs and fewer construction days
- Enhances safety by eliminating handling of steel fibers, welded wire fabrics or light rebar
- Eliminates concerns of proper positioning of reinforcement
- Provides superior crack control due to the geometry and elastic modulus
- Abrasion resistance and will not corrode
- Controls plastic and drying shrinkage cracks

Addition Rates

STRUX 90/40 addition rates are dependent on the specific application and desired properties and will vary between 3.0 to 12.0 lbs/yd^3 (1.8 to 7.0 kg/m^3).

Mix Design

The utilization of STRUX 90/40 may require the use of a superplasticizer such as ADVA® to restore the required workability. In addition, slight increases in fine aggregate contents may be needed.

STRUX 90/40 may be added to concrete at any point during the batching or mixing process. After fiber addition, the concrete must be mixed at the minimum of 70 revolutions to ensure adequate dispersion.

Please contact your Grace representative with any questions. For more detailed instructions refer to Technical Bulletin TB-1200.

CLASSIFIED c UL US

STRUX® 90/40 fiber as marketed by W. R. Grace & Co.–Conn. is classified by Underwriters Laboratories Inc. for use as an alternative, or in addition to, the welded wire fabric in 1, 1½ and 2 hr floor-ceiling D700, F700, D800, F800, D900 and F900 (except 909) Series Designs. Fibers to be added to the concrete mix at maximum addition rate of 5 lbs/yd^3 (3.0 kg/m^3).

Compatibility with Other Admixtures and Batch Sequencing

STRUX 90/40 is compatible with all Grace admixtures. Their action in concrete is mechanical and will not affect the hydration process of the cement or compressive strength. Each liquid admixture should be added separately to the concrete mix.

Packaging

STRUX 90/40 is available in 1.0 lb or 5.0 lb (.5 kg or 2.3 kg) Concrete-Ready™ bags.

STRUX 90/40 Properties

Specific gravity	0.92
Absorption	None
Modulus of elasticity	1,378 ksi (9.5 GPa)
Tensile strength	90 ksi (620 MPa)
Melting point	320°F (160°C)
Ignition point	1,094°F (590°C)
Alkali, acid & salt resistance	High

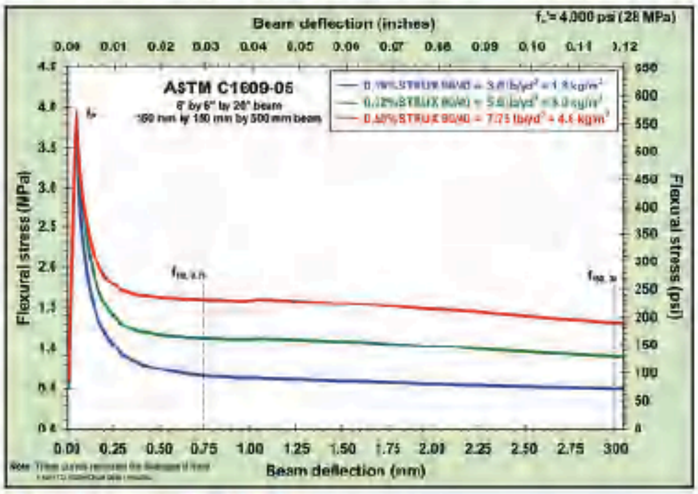
Flexural Strength and Toughness (Compressive Strength: 4,000 psi) according to ASTM C1609-05

STRUX 90/40 Dosage Rate	Specimen cross-section		Peak Load P_P (lbf)	Peak Strength f_P (psi)	Peak-load deflection δ_P (in.)	Residual loads		Residual strengths		Toughness T^D_{150} (lbf-in.)	JCI-SF4[1] $f_{b,e}$ (psi)	TR34[2] $R_{e,3}$ (%)
	Width (in.)	Depth (in.)				P^D_{600} (lbf)	P^D_{150} (lbf)	f^D_{600} (psi)	f^D_{150} (psi)			
0.19% (3.0 lbs/yd³)	6.00	5.95	6,702	565	0.0019	1,299	982	110	80	160	115	20.0%
0.32% (5.0 lbs/yd³)	6.00	6.00	7,064	595	0.0020	1,905	1,555	160	130	240	165	28.5%
0.50% (7.75 lbs/yd³)	6.00	5.95	6,860	580	0.0020	2,770	2,251	230	190	330	230	40.5%

Flexural Strength and Toughness (Compressive Strength: 28 MPa) according to ASTM C1609-05

STRUX 90/40 Dosage Rate	Specimen cross-section		Peak Load P_P (N)	Peak Strength f_P (MPa)	Peak-load deflection δ_P (mm)	Residual loads		Residual strengths		Toughness T^D_{150} (Joule)	JCI-SF4[1] $f_{b,e}$ (MPa)	TR34[2] $R_{e,3}$ (%)
	Width (mm)	Depth (mm)				P^D_{600} (N)	P^D_{150} (N)	f^D_{600} (MPa)	f^D_{150} (MPa)			
0.19% (1.8kg/m³)	152	151	29,813	3.90	0.048	5,776	4,236	0.75	0.55	18	0.80	20.0%
0.32% (3.0kg/m³)	152	152	31,422	4.10	0.050	8,472	6,932	1.10	0.90	27	1.15	28.5%
0.50% (4.6kg/m³)	152	151	30,513	4.00	0.050	12,323	10,012	1.60	1.30	37	1.60	40.5%

1) Japan Concrete Institute (JCI) Standard Test Method for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete (Standard SF4), JCI Standards for Test Methods of Fiber Reinforced Concrete, Japan Concrete Institute, 1983 2) The Concrete Society Technical Report 34 Concrete industrial ground floors—A guide to their design and construction, The Society, Crowthorne, 2003



www.graceconstruction.com

North American Customer Service: 1-877-4AD-MIX1 (1-877-423-6491)

STRUX-5M Printed in U.S.A. 11/07 FA/LI/1M

Grace Concrete Products

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STRUX® BT50
Synthetic Macro Fiber

Product Description

STRUX® BT50 synthetic macro fiber reinforcement is a high strength, high modulus synthetic macro reinforcement that imparts toughness, impact and fatigue properties to concrete. STRUX BT50 is a patented engineered design providing superior post-crack control performance with a broad range of applications. STRUX BT50 reinforced concrete reliably achieves residual strength values in excess of 145 psi for every 4.5 lbs/yd³ (1 MPa for every 2.7 kg/m³). STRUX BT50 fibers are 2 in. (50 mm) in length with an aspect ratio of 75 and are primarily designed to replace steel fibers, welded wire fabric, light rebar and other select secondary reinforcement in slab-on-ground flooring. STRUX BT50 is a user friendly fiber reinforcement which is easier and safer to use, compared to other types of reinforcement.

Product Advantages

- Unique packaging provides superior dispersion
- Savings from reduced labor costs and shorter construction time
- Enhances safety by eliminating handling of steel fibers, welded wire fabric or rebar
- Eliminates proper reinforcement positioning concerns
- Provides superior crack control due to the geometry and elastic modulus
- Non corroding
- Controls both plastic and drying shrinkage
- Increased crack resistance, ductility and energy absorption or toughness
- Improved impact resistance

Uses

STRUX BT50 is engineered for ease of use, excellent dispersion and finishability in slab-on-ground flooring applications. STRUX BT50 can be used in commercial, industrial and manufacturing floors, along with other select flat and form work applications. STRUX BT50 is also ideal for use in precast tunnel segments and other select precast applications, pavements and soil stabilization projects, shotcrete and blast resistance. Please consult your Grace sales representative to discuss your specific application.

Addition Rates

STRUX BT50 addition rates are dependent on the specific application and desired properties and will typically vary between 7 to 15 lbs/yd³ (4.0 to 9.0 kg/m³).

Guidelines for Usage and Compatibility with Other Admixtures

STRUX BT50 is fully compatible with the complete line of Grace admixtures. STRUX BT50 action in concrete is mechanical and will not affect the cement hydration process. Slight mix design modifications including increases in fine aggregate contents and high range water reducer dosage rates may be required when incorporating STRUX BT50 into a mix design. Each additional 3 - 4 lbs/yd³ (1.8 - 2.4 kg/m³) of STRUX BT50 may reduce the slump of the concrete approximately 1 in. (25 mm).

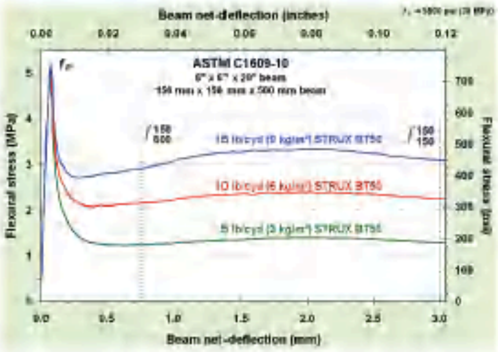
Up front addition of STRUX BT50 into empty drums prior to batching provides optimal STRUX BT50 dispersion in the concrete mixture. However, STRUX BT50 may be added to the concrete at any point during the batching or mixing process. STRUX BT50 should be mixed a minimum of 70 revolutions as specified in ASTM C94. Please consult with your Grace representative and refer to Technical Bulletin TB-1205 for further detail.

Packaging

STRUX BT50 is available in 10 lb (4.5 kg) bags.

STRUX BT50 Properties

Specific gravity	0.91
Absorption	None
Modulus of elasticity	1,000 ksi (7 GPa)
Tensile strength	80 ksi (550 MPa)
Melting point	320°F (160°C)
Ignition point	1,050°F (570°C)
Alkali, acid & salt resistance	High



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North American Customer Service: 1-877-4AD-MIX1 (1-877-423-6491)

STRUX-72 Printed in U.S.A. 2/11 FA/PDF

APPENDIX A4

Acryl

ÍMÚR AKRÝL 100 alkalíþolin plastþeyta

NOTKUNARSVIÐ:

Íblöndunarefni fyrir þunnhúðir, viðgerðarefni, múr og steypu. Akrýl 100 hentar vel til íblöndunar í þunnar ílagnir og pússlög, til að auka viðloðun múrhúða og ílagna og til að auka límhæfni múrblanda.

EFNISLÝSING:

ÍMÚR Akrýl 100 er fínkorna, meðalþykk vatnsþeyta með háum stöðugleika. Þeytan myndar mjúka, teygjanlega og gagnsægja húð, við hitastig yfir 5°C. Hægt er að lækka húðmyndunarhitastig með íblöndun t.d. bútylglykols eða bútylglykolacetats. Akrýl 100 hefur mikið og gott vatns- og alkalíþol. Þeytunni má blanda saman við sement, kalk og gips og gefur hún blöndunni mýkt, þjálni og eykur viðloðun og togstyrk hennar.

TÆKNILEGAR UPPLÝSINGAR:

Fjölliðategund	Akrýlat
Þurrefni	48%
Hjálparefni	Yfirborðsvirk efni
Sýrustig pH	7,5–8,5
Lægsta húðmyndunarhitastig	5°C
Frostþol	-5°C

BLÖNDUN/NOTKUN:

Til að grunna undirlag
Í sementsblöndu: Sement:sandur 1:1 hrærist út kústanlegur vellingur með upplausninni 1:1 til 1:2. Akrýl 100:vatn. Í stað sands-/sementsblöndu er líka hægt að nota ÍMÚR-viðgerðarefni.

Til íblöndunar
Steypu-, múr- og viðgerðarblöndur hrærast út með 1:3 til 1:10. Akrýl 100:vatn.

September 1999

BM Vallá ehf
Breiðhöfða 3
110 Reykjavík

Sími: 412 5050
Fax: 412 5001
sala@bmvalla.is

BM·VALLÁ

bmvalla.is

APPENDIX A5

Super plasticizer

www.omnicon.com

OMNICON Color- and Technologycenter

Procon SPC 25 (FM)

Superplasticizer for concrete according to EN 934-2: T 3.1/3.2
CE – 0402 – CPD – 37 83 01

Procon SPC 25 (FM) is a flux substance based on a combination of highly effective raw materials to ready-mix concrete production plants. It is designed to produce a fluid concrete as a F5/F6 slump. Opposite to conventional high-end flux substances, **Procon SPC 25 (FM)** ensures an obviously better dispersion of cement particles. Due to it´s molecular structure **Procon SPC 25 (FM)** ensures a very good and long lasting workability. The usage of **Procon SPC 25 (FM)** leads to good final results as strength, density and durability.

Advantages: Due to it´s distinct liquefaction feature **Procon SPC 25 (FM)** is very well suitable to be used as flux substance within the ready-mix concrete plants. Due to it´s active substance combination **Procon SPC 25 (FM)** can ensure a long lasting workability, also in concrete mixes with very low w/c ratios (<0,40).

Method of use: Optimal concrete plasticizing effect is obtained if **Procon SPC 25 (FM)** is added into the concrete mix right after the addition of the first 50 - 70% of the mixing water. Avoid adding **Procon SPC 25 (FM)** to dry aggregates. **Procon SPC 25 (FM)** is compatible with Procon **SPL (LP)** to produce frost-thaw salt resistant concrete. When a combination of products is used, this must be evaluated first.

Dosage: The normally recommended dosage rate is between 0,50 – 1,80% of cement (binder) depending on specific mix design and requirements. Other dosages may be recommended in special cases according to specific job conditions.

Technical data:

Colour:	yellowish
Appearance:	liquid
Active matter:	Polycarboxylatether
Storage and stability:	The product can be kept for 1 year when stored in a dry place, in the closed original packaging, at temperatures between +5 and +30°C.
Freezing point:	0°C
Packaging:	25L can, 200L drum, 1000L container

Technical specification:

Properties	Method	Value
Density at 20°C	DS/ISO 758	1,08 +/- 0,020kg/L
Solid content	ASTM C 494	33,0 +/- 1,9%
Äquivalent Na_2O	DS/EN 480-12	<0,50%
Chloride content	DS/EN 480-10	<0,10%
pH-Value	ISO 4316	5,9 +/-1,0

Precautions: According to the Ministry of the Environment notice no. 329 from 2002-05-16 the product must not be labelled. Gloves for protection and goggles should be used. Skin that has been in contact with the product must immediately be flushed with water. If the product gets into contact with your eyes, flush with water, if irritation persists seek medical attention.
For detailed information please see Material Safety Data Sheet.

Remarks: Our recommendations must be considered as guidelines. Individual testing is necessary in order to ensure optimal use of the product.

Technical support: Consult our technical service team for assistance in special mix designs.

The information and the recommendations in this publication are to the best of our knowledge reliable. However, nothing herein is to be construed as a warranty or representation. Users should make their own tests to determine the applicability of such information or the suitability of any products for their own particular purpose.

Date: 2007-11-20

Technical Data Sheet Procon SPC 25 (FM)
Version 1. EN-Norm

APPENDIX B

Results of compressive strength, group a

Compressive strength of beam specimens in group a

Sample (Hydrat. time in days)	Sample dimensions [mm] Width			average	Height	Weight [kg] bef. Testing	Density [kg/m³] before testing	Load [kg]	Compressive strength Mpa	Average	STD	COV
1	100.50	100.50	100.60	100.13	203.50	3.59	2241	6600	8			
	98.85	100.30	100.00									
1	99.90	99.60	99.40	99.37	200.00	3.50	2257	6650	8			
	98.95	99.20	99.15									
1	99.50	100.00	99.20	99.35	200.00	2.52	2270	6800	8	8	0.18	2.3
	99.20	99.10	99.10									
7	99.70	98.90	100.45	99.49	199.95	3.56	2290	19500	24			
	99.30	99.30	99.30									
7	98.90	98.60	100.50	99.63	199.90	3.61	2317	20200	25			
	100.00	100.00	99.75									
7	100.11	99.90	100.50	100.74	200.00	3.68	2309	21200	25	25	0.72	2.9
	100.70	101.60	101.60									
28	101.00	102.00	100.00	101.17	200.00	3.64	2264	24500	29			
	100.00	102.00	102.00									
28	100.00	100.20	100.00	100.05	200.20	3.65	2319	25500	31			
	99.80	100.00	100.30									
28	99.60	99.40	99.80	99.40	200.00	3.59	2313	27000	33	31	2.05	6.6
	99.40	99.20	99.00									

Results of compressive strength, group b

Compressive strength of beam specimens in group b

Sample (Hydrat. time in days)	Sample dimensions [mm] Width			average	Height	Weight [kg] bef. Testing	Density [kg/m³] before testing	Load [kg]	Compressive strength Mpa			
1	100.00 99.10	98.30 99.80	99.30 99.80	99.38	200.80	3.61	2318	3700	5			
1	100.00 99.70	98.90 99.90	100.70 100.00	99.87	200.30	3.61	2301	3950	5			
1	101.20 101.30	100.40 102.00	101.20 101.40	101.25	200.80	3.70	2289	3700	4	**Average** 5	**STD** 0.21	COV 4.7
7	100.00 99.90	99.30 99.70	100.50 100.00	99.90	200.20	3.65	2326	14600	18			
7	100.60 99.70	99.60 99.70	99.80 99.60	99.83	202.40	3.65	2304	13800	17			
7	100.60 101.50	100.60 101.00	100.20 100.70	100.77	200.40	3.73	2334	18300	22	**Average** 19	**STD** 2.69	COV 14.3
28	100.00 99.50	98.90 99.10	100.00 98.80	99.38	200.00	3.59	2314	24100	30			
28	101.60 100.70	100.30 101.00	101.30 101.00	100.98	200.00	3.72	2322	25400	30			
28	101.30 101.30	100.20 100.90	101.30 101.00	101.00	200.80	3.72	2312	25350	30	**Average** 30	**STD** 0.34	COV 1.1

Results of compressive strength, group c

Compressive strength for beam specimens in group c

Sample (Hydrat. time in days)	Sample dimensions [mm] Width			average	Height	Weight [kg] bef. Testing	Density [kg/m³] before testing	Load [kg]	Compressive strength Mpa			
1	99.90	99.90	100.00	100.05	200.20	3.67	2332	13450	16			
	100.10	100.00	100.40									
1	99.30	99.20	99.00	99.15	200.50	3.68	2377	14050	17			
	99.20	99.10	99.10									
1	99.60	99.90	100.10	99.83	200.40	3.65	2327	13150	16	**Average**	**STD**	COV
	100.40	99.40	99.60							16	0.70	4.2
7	100.00	99.40	100.00	99.40	200.50	3.70	2378	40200	49			
	99.00	99.00	99.00									
7	100.00	100.10	100.40	100.07	200.30	3.72	2362	40800	49			
	100.00	100.00	99.90									
7	99.50	99.20	98.90	99.40	200.00	3.65	2352	38800	47	**Average**	**STD**	COV
	99.30	99.50	100.00							49	1.01	2.1
28	99.00	99.00	99.00	99.20	200.40	3.65	2356.58	45800	56			
	99.70	99.20	99.30									
28	99.00	100.80	100.50	100.13	200.30	3.74	2371.06	50800	61			
	100.30	100.00	100.20									
28	99.30	99.40	99.30	99.10	201.00	3.71	2392.99	40400	50	**Average**	**STD**	COV
	98.70	98.80	99.10							56	5.78	10.4

Results of compressive strength, small-scale beams

Compressive strength of small-scale beams

Sample (Hydrat. time in days)	Sample dimensions [mm] Width			average	Height	Weight [kg] bef. Testing	Density [kg/m³] before testing	Load [kg]	Compressive strength Mpa	Average	STD	COV
56	100.20	100.00	100.00	100.13	200.40	3.87	2452	47200	60			
	100.00	100.00	100.60									
56	100.00	100.00	99.80	99.98	200.40	3.87	2460	39900	51			
	100.10	99.30	100.70									
56	100.20	100.00	99.60	100.03	200.60	3.86	2448	46600	59	57	5.09	9.0
	100.10	100.00	100.30									

APPENDIX C

Modulus of elasticity for group a

Nýsköpunarmiðstöð Íslands Íslenskar byggingartæknirannsóknir	Rannsókn nr: 1 Dags: 11.11.2011 Frkv. af: SLS

Fjaðurstuðull steinsteypu s.k.v. ISO 6784

Unnið fyrir: MSc verkefni SLS

Steypudagur: 13.10.2011

Sýni Nr.	Aldur Dagar	Prófunar-álag MPa	Hlutfalls. álag %	Þrýstiþol MPa	Fjaður-stuðull GPa	Fjaðurst. meðaltal GPa	Staðal-frávik GPa
1	28	9.4	0.33	28.6	25.6		
2	28	9.6	0.29	33.4	26.7		
3	28	10.1	0.29	35.4	28.0	**26.8**	**1.2**

Modulus of elasticity for group b

Nýsköpunarmiðstöð Íslands Íslenskar byggingartæknirannsóknir	Rannsókn nr: 2 Dags: 12.01.2012 Frkv. af: SLS

Fjaðurstuðull steinsteypu s.k.v. ISO 6784

Unnið fyrir: MSc verkefni SLS

Steypudagur: 14.12.2011

Sýni Nr.	Aldur Dagar	Prófunar-álag MPa	Hlutfalls. álag %	Þrýstiþol MPa	Fjaður-stuðull GPa	Fjaðurst. meðaltal GPa	Staðal-frávik GPa
2	28	9.0	0.31	29.0	27.7		
3	28	8.3	0.29	29.3	32.2		
4	28	8.5	0.28	30.4	28.1	**29.3**	**2.5**

Modulus of elasticity for group c

Nýsköpunarmiðstöð Íslands Íslenskar byggingartæknirannsóknir	Rannsókn nr: 3 Dags: 29.03.2012 Frkv. af: SLS

Fjaðurstuðull steinsteypu s.k.v. ISO 6784

Unnið fyrir: MSc verkefni SLS

Steypudagur: 28.02.2012

Sýni Nr.	Aldur Dagar	Prófunar-álag MPa	Hlutfalls. álag %	Þrýstiþol MPa	Fjaður-stuðull GPa	Fjaðurst. meðaltal GPa	Staðal-frávik GPa
2	32	25.4	0.43	59.3	34.3		
3	32	24.6	0.50	49.3	32.7		
4	32	23.4	0.38	62.2	33.6	**33.5**	**0.8**

APPENDIX D

Results from flexural and compression testing on CBM materials

Mix	1.3% SP			1.6% SP			1.9% SP		
Sample - 2 day strength	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Bending M Force (kg)	278	270	236	236	232	245	235	229	271
Max. Bending Moment (Nm)	68.2	66.2	57.9	57.9	56.9	60.1	57.6	56.2	66.5
Max. Tensile force N	3409.0	3310.9	2894.0	2894.0	2844.9	3004.3	2881.7	2808.1	3323.1
Max. Tensile stress (MPa)	**6.4**	**6.2**	**5.4**	**5.4**	**5.3**	**5.6**	**5.4**	**5.3**	**6.2**
Mean (MPa)		6.0			5.5			5.6	
Standard dev. (MPa)		0.5			0.2			0.5	
Coefficient of var. (%)		8.5			2.8			9.3	
Compressive Force (kg)	8130 8240	7770 7810	7800 8030	7000 7070	7090 7670	7600 7470	6600 6520	6500 6120	6420 6710
Compressive strength (MPa)	65	62	63	56	59	60	52	50	52
Mean (MPa)		63.4			58.2			51.6	
Standard dev. (MPa)		1.6			2.0			1.2	
Coefficient of var. (%)		2.5			3.5			2.3	

Mix	10% SF			12% SF			15% SF		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	218	245	228	253	230	217	219	255	235
Max. Bending Moment (Nm)	53.5	60.1	55.9	62.0	56.4	53.2	53.7	62.5	57.6
Max. Tensile force N	2673.2	3004.3	2795.9	3102.4	2820.4	2661.0	2685.5	3126.9	2881.7
Max. Tensile stress (MPa)	**5.0**	**5.6**	**5.2**	**5.8**	**5.3**	**5.0**	**5.0**	**5.9**	**5.4**
Mean (MPa)		5.3			5.4			5.4	
Standard dev. (MPa)		0.3			0.4			0.4	
Coefficient of var. (%)		5.9			7.8			7.6	
Compressive Force (kg)	9030 8900	9070 9130	8570 8610	8660 8270	8740 8400	9200 9120	8180 8810	8870 8970	8900 8710
Compressive strength (MPa)	71	72	68	67	68	73	68	71	70
Mean (MPa)		70.7			69.5			69.6	
Standard dev. (MPa)		2.1			3.0			1.7	
Coefficient of var. (%)		3.0			4.3			2.5	

Mix	0.25% STRUX 90/40			0.50% STRUX 90/40			0.75% STRUX 90/40		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	269	266	275	239	263	256	245	277	277
Max. Bending Moment (Nm)	66.0	65.2	67.4	58.6	64.5	62.8	60.1	67.9	67.9
Max. Tensile force N	3298.6	3261.8	3372.2	2930.7	3225.0	3139.2	3004.3	3396.7	3396.7
Max. Tensile stress (MPa)	**6.2**	**6.1**	**6.3**	**5.5**	**6.0**	**5.9**	**5.6**	**6.4**	**6.4**
Mean (MPa)		6.2			5.8			6.1	
Standard dev. (MPa)		0.1			0.3			0.4	
Coefficient of var. (%)		1.7			4.9			6.9	
Compressive Force (kg)	8890 7980	9200 9190	8826 8480	8560 8280	7710 8470	8150 7680	7590 7270	7360 6190	7440 7430
Compressive strength (MPa)	67	73	69	67	64	63	59	54	59
Mean (MPa)		69.7			64.8			57.4	
Standard dev. (MPa)		3.1			2.0			3.0	
Coefficient of var. (%)		4.5			3.1			5.3	

Mix	0.25% STRUX BT50			0.50% STRUX BT50			0.75% STRUX BT50		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	249	274	294	377	321	277	280	280	484
Max. Bending Moment (Nm)	61.1	67.2	72.1	92.5	78.7	67.9	68.7	68.7	118.7
Max. Tensile force N	3053.4	3359.9	3605.2	4623.0	3936.3	3396.7	3433.5	3433.5	5935.1
Max. Tensile stress (MPa)	**5.7**	**6.3**	**6.8**	**8.7**	**7.4**	**6.4**	**6.4**	**6.4**	**11.1**
Mean (MPa)		6.3			7.5			8.0	
Standard dev. (MPa)		0.5			1.2			2.7	
Coefficient of var. (%)		8.3			15.4			33.8	
Compressive Force (kg)	8130 8190	8520 7970	8470 7990	7360 7900	7880 8190	7620 7880	7760 7680	7730 7720	7780 7740
Compressive strength (MPa)	65	66	65	61	64	62	61	61	62
Mean (MPa)		65.3			62.1			61.6	
Standard dev. (MPa)		0.4			1.7			0.2	
Coefficient of var. (%)		0.6			2.7			0.3	

Mix	11% Acryl			22% Acryl			33% Acryl		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	112	116	127.1	115.4	103.1	101.2	107.8	119.7	115.3
Max. Bending Moment (Nm)	27.5	28.4	31.2	28.3	25.3	24.8	26.4	29.4	28.3
Max. Tensile force N	1373.4	1422.5	1558.6	1415.1	1264.3	1241.0	1321.9	1467.8	1413.9
Max. Tensile stress (MPa)	**2.6**	**2.7**	**2.9**	**2.7**	**2.4**	**2.3**	**2.5**	**2.8**	**2.7**
Mean (MPa)		2.7			2.5			2.6	
Standard dev. (MPa)		0.2			0.2			0.1	
Coefficient of var. (%)		6.6			7.2			5.3	
Compressive Force (kg)	1682 1795	1777 1708	1772 1666	1712 1566	1670 1661	1602 1591	1953 1860	1891 1915	1837 1862
Compressive strength (MPa)	14	14	14	13	13	13	15	15	15
Mean (MPa)		13.8			13.0			15.0	
Standard dev. (MPa)		0.1			0.3			0.3	
Coefficient of var. (%)		0.7			2.1			1.7	

Mix	11% Acryl 0.4% SP			22% Acryl 0.4% SP			33% Acryl 0.4% SP		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	212	225	195.9	168	195.3	179.3	168.5	183.4	154.4
Max. Bending Moment (Nm)	52.0	55.2	48.0	41.2	47.9	44.0	41.3	45.0	37.9
Max. Tensile force N	2599.7	2759.1	2402.2	2060.1	2394.9	2198.7	2066.2	2248.9	1893.3
Max. Tensile stress (MPa)	**4.9**	**5.2**	**4.5**	**3.9**	**4.5**	**4.1**	**3.9**	**4.2**	**3.5**
Mean (MPa)		4.9			4.2			3.9	
Standard dev. (MPa)		0.3			0.3			0.3	
Coefficient of var. (%)		6.9			7.6			8.6	
Compressive Force (kg)	4630 4700	4680 4720	4600 4480	4050 3800	3990 3950	3860 4090	3760 3820	3550 3440	3890 3730
Compressive strength (MPa)	37	37	36	31	32	32	30	28	30
Mean (MPa)		36.9			31.5			29.4	
Standard dev. (MPa)		0.7			0.2			1.4	
Coefficient of var. (%)		1.8			0.7			4.8	

Mix	Small-scale beams SP			Small-scale beams BT50			Small-scale beams Acryl		
Sample - 2 day strength	1	2	3	1	2	3	1	2	3
Bending M Force (kg)	363	365	323	262	260	247	97.9	98.9	111
Max. Bending Moment (Nm)	89.0	89.5	79.2	64.3	63.8	60.6	24.0	24.3	27.2
Max. Tensile force N	4451.3	4475.8	3960.8	3212.8	3188.3	3028.8	1200.5	1212.8	1361.1
Max. Tensile stress (MPa)	**8.3**	**8.4**	**7.4**	**6.0**	**6.0**	**5.7**	**2.3**	**2.3**	**2.6**
Mean (MPa)		8.1			5.9			2.4	
Standard dev. (MPa)		0.5			0.2			0.2	
Coefficient of var. (%)		6.8			3.2			7.1	
Compressive Force (kg)	9830 9840	9950 9970	9390 9690	7440 7720	8210 7930	7750 8070	1949 1630	2230 1816	1866 1857
Compressive strength (MPa)	78	79	76	60	64	63	14	16	15
Mean (MPa)		77.8			62.5			15.1	
Standard dev. (MPa)		1.7			2.0			1.0	
Coefficient of var. (%)		2.2			3.2			6.3	

Mix	Final mix SP			Final mix BT50			Final mix Acryl		
Sample - 2 day strength	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Bending M Force (kg)	403	397	345	405	321	449	0	214	168
Max. Bending Moment (Nm)	98.8	97.4	84.6	99.3	78.7	110.1	0.0	52.5	41.2
Max. Tensile force N	4941.8	4868.2	4230.6	4966.3	3936.3	5505.9	0.0	2624.2	2060.1
Max. Tensile stress (MPa)	**9.3**	**9.1**	**7.9**	**9.3**	**7.4**	**10.3**	**0.0**	**4.9**	**3.9**
Mean (MPa)		8.8			9.0			2.9	
Standard dev. (MPa)		0.7			1.5			2.6	
Coefficient of var. (%)		8.4			16.6			88.5	
Compressive Force (kg)	10190 10330	10380 10080	10180 10350	11150 11380	11090 11320	11300 10910	1949 1630	2230 1816	1866 1857
Compressive strength (MPa)	82	81	82	90	89	88	14	16	15
Mean (MPa)		81.6			89.1			15.1	
Standard dev. (MPa)		0.2			0.6			1.0	
Coefficient of var. (%)		0.2			0.7			6.3	

Mix	Final mix SP			Final mix BT50			Final mix Acryl		
Sample - 14 day strength	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Bending M Force (kg)	392	352	332	460	417	454	313	333	302
Max. Bending Moment (Nm)	96.1	86.3	81.4	112.8	102.3	111.3	76.8	81.7	74.1
Max. Tensile force N	4806.9	4316.4	4071.2	5640.8	5113.5	5567.2	3838.2	4083.4	3703.3
Max. Tensile stress (MPa)	**9.0**	**8.1**	**7.6**	**10.6**	**9.6**	**10.4**	**7.2**	**7.7**	**6.9**
Mean (MPa)		8.2			10.2			7.3	
Standard dev. (MPa)		0.7			0.5			0.4	
Coefficient of var. (%)		8.5			5.2			5.0	
Compressive Force (kg)	16360 17210	16610 16490	16550 17600	16890 16440	17840 14840	16560 16640	7630 7930	8575 8270	7880 7290
Compressive strength (MPa)	134	132	136	133	130	132	62	67	60
Mean (MPa)		133.7			131.6			63.1	
Standard dev. (MPa)		2.1			1.4			3.5	
Coefficient of var. (%)		1.6			1.0			5.5	

APPENDIX E

Calculations

	ACI 318-08			
Group:	a and b	$V_c = 0.17 \sqrt{f_c}\, b\, d$		
Shear strength of concrete		V_c	28.7	kN

Standard:	EN 1992-1-1:2004			
Group:	a and b	$V_c = \tau_r\, k(1.2+40\rho_{s2}) b\, d$		
Mean concrete tensile strength		f_{ctm}	3.0	$0.3 f_c^{2/3}$
Mean resisting shear strength		τ_r	0.74012043	$0.25 f_{ctm}$
Constant		k	1.4	$1.6 - d \geq 1$
Shear strength of concrete		V_c	30.3	kN

Standard:	ACI 440			
Group:	a	Beam nr.	BSa3 and BSa4	
Fibre used:	BAS UNI 600			
Beam		Notation	Size	Unit
Width		b	150	mm
Height		h	250	mm
Lengt		L	2500	mm
Concrete cover		d_{cover}	40	mm
Effective depth		d	202	mm
Area of concrete		A_c	37500	mm^2
Concrete				
Compressive strength		f_c	31	MPa
Modulus of elasticity		E_c	27000	MPa
Steel reinforcement				
Steel compressive bars		$Ø_1$	6	mm
Number of compressive bars		K6	2	psc.
Steel compressive reinforcement ratio		ρ_{s1}	0.2	0.2%
Area of compressive reinforcement		A_{s1}	57	mm^2
Steel tensile bars		$Ø_2$	16	mm
Number of tensile bars		K16	2	psc.
Steel tensile reinforcement ratio		ρ_{s2}	0.013	1.30%
Area of tensile reinforcement		A_{s2}	402	mm^2
Yield strength		f_y	500	MPa
Modulus of elasticity		E_s	210000	MPa
BFRP external reinforcement				
Thickness		t_f	0.65	mm
Width		s_f	400	mm
Number of layers		n	1	-
Fibre alignment		β	90	°
Area of FRP		A_f	520	mm^2
FRP reinforcement ratio		ρ_f	0.017	1.7%
Modulus of elasticity		E_f	26800	MPa
Ultimate tensile strength		f_f	588.2	MPa
Ultimate tensile strain		ε_f	0.027	2.7%
Shear strengthening calculations				
Effective lengt of FRP		L_e	81	mm
Modafication factor		k_1	1.1	-
Modafication factor (U-wrapped)		k_2	0.60	-
Strain-reduction factor		k_v	0.17	-
Effective strain (U-wrapped)		ε_{fe}	0.0045	$k_v*\varepsilon_{fu}<0{,}004$
Allowable strain by ACI		ε_{fe}	0.004	0.4%
Effective tensile stress		f_{fe}	107	MPa
Shear contribution of FRP		V_f	28.2	kN

Standard: ACI 440				
Group: a	Beam nr.	BSa5 and BSa6		
Fibre used: BAS BI 450				
Beam		Notation	Size	Unit
Width		b	150	mm
Height		h	250	mm
Lengt		L	2500	mm
Concrete cover		d_{cover}	40	mm
Effective depth		d	202	mm
Area of concrete		A_c	37500	mm^2
Concrete				
Compressive strength		f_c	31	MPa
Modulus of elasticity		E_c	27000	MPa
Steel reinforcement				
Steel compressive bars		$Ø_1$	6	mm
Number of compressive bars		K6	2	psc.
Steel compressive reinforcement ratio		ρ_{s1}	0.2	0.2%
Area of compressive reinforcement		A_{s1}	57	mm^2
Steel tensile bars		$Ø_2$	16	mm
Number of tensile bars		K16	2	psc.
Steel tensile reinforcement ratio		ρ_{s2}	0.013	1.30%
Area of tensile reinforcement		A_{s2}	402	mm^2
Yield strength		f_y	500	MPa
Modulus of elasticity		E_s	210000	MPa
BFRP external reinforcement				
Thickness		t_f	0.45	mm
Width		s_f	400	mm
Number of layers		n	1	-
Fibre alignment		β	45	°
Area of FRP		A_f	360	mm^2
FRP reinforcement ratio		ρ_f	0.012	1.2%
Modulus of elasticity		E_f	25900	MPa
Ultimate tensile strength		f_f	50.3	MPa
Ultimate tensile strain		ε_f	0.007	0.7%
Shear strengthening calculations				
Effective lengt of FRP		L_e	102	mm
Modafication factor		k_1	1.1	-
Modafication factor (U-wrapped)		k_2	0.49	-
Strain-reduction factor		k_v	0.66	k_v<0,75
Allowable strain-reduction factor by ACI		k_v	0.75	
Effective strain (U-wrapped)		ε_{fe}	0.0053	k_v*ε_{fu}<0,004
Allowable strain by ACI		ε_{fe}	0.004	0.4%
Effective tensile stress		f_{fe}	104	MPa
Shear contribution of FRP		V_f	26.6	kN

Standard:	ACI 440			
Group:	a	Beam nr.	BSa7 and BSa8	
Fibre used:	BAS BI 450			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	202	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	31	MPa
Modulus of elasticity	E_c	27000	MPa
Steel reinforcement			
Steel compressive bars	$Ø_1$	6	mm
Number of compressive bars	K6	2	psc.
Steel compressive reinforcement ratio	ρ_{s1}	0.2	0.2%
Area of compressive reinforcement	A_{s1}	57	mm^2
Steel tensile bars	$Ø_2$	16	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_{s2}	0.013	1.30%
Area of tensile reinforcement	A_{s2}	402	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.45	mm
Width	s_f	400	mm
Number of layers	n	3	-
Fibre alignment	β	45	°
Area of FRP	A_f	1080	mm^2
FRP reinforcement ratio	ρ_f	0.036	3.6%
Modulus of elasticity	E_f	26500	MPa
Ultimate tensile strength	f_f	190.6	MPa
Ultimate tensile strain	ε_f	0.032	3.2%
Shear strengthening calculations			
Effective lengt of FRP	L_e	101	mm
Modafication factor	k_1	1.1	-
Modafication factor (U-wrapped)	k_2	0.50	-
Strain-reduction factor	k_v	0.15	k_v<0,75
Effective strain (U-wrapped)	ε_{fe}	0.0047	$k_v*\varepsilon_{fu}$<0,004
Allowable strain by ACI	ε_{fe}	0.004	0.4%
Effective tensile stress	f_{fe}	106	MPa
Shear contribution of FRP	V_f	81.8	kN

Standard:	ACI 440			
Group:	b	Beam nr.	BSb4 and BSb6	
Fibre used:	BAS BI 450			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	202	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	30	MPa
Modulus of elasticity	E_c	29000	MPa
Steel reinforcement			
Steel compressive bars	$Ø_1$	6	mm
Number of compressive bars	K6	2	psc.
Steel compressive reinforcement ratio	ρ_{s1}	0.2	0.2%
Area of compressive reinforcement	A_{s1}	57	mm^2
Steel tensile bars	$Ø_2$	16	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_{s2}	0.013	1.30%
Area of tensile reinforcement	A_{s2}	402	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.45	mm
Width	s_f	400	mm
Number of layers	n	3	-
Fibre alignment	β	45	°
Area of FRP	A_f	1080	mm^2
FRP reinforcement ratio	ρ_f	0.036	3.6%
Modulus of elasticity	E_f	25900	MPa
Ultimate tensile strength	f_f	190.6	MPa
Ultimate tensile strain	ε_{fu}	0.032	3.2%
Shear strengthening calculations			
Effective strain (0-wrapped)	ε_{fe}	0.0240	$=0.004 \leq 0.75\varepsilon_{fu}$
Allowable strain by ACI	ε_{fe}	0.004	0.4%
Effective tensile stress	f_{fe}	104	MPa
Shear contribution of FRP	V_f	79.9	kN

Standard:	TR55		
Group:	a	Beam nr.	BSa3 and BSa4
Fibre used:	BAS UNI 600		

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	202	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	31	MPa
Modulus of elasticity	E_c	27000	MPa
Steel reinforcement			
Steel compressive bars	$Ø_1$	6	mm
Number of compressive bars	K6	2	psc.
Steel compressive reinforcement ratio	ρ_{s1}	0.2	0.2%
Area of compressive reinforcement	A_{s1}	57	mm^2
Steel tensile bars	$Ø_2$	16	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_{s2}	0.013	1.30%
Area of tensile reinforcement	A_{s2}	402	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.65	mm
Width	s_f	400	mm
Number of layers	n	1	-
Fibre alignment	β	90	°
Area of FRP	A_f	520	mm^2
FRP reinforcement ratio	ρ_f	0.017	3.6%
Modulus of elasticity	E_f	26800	MPa
Ultimate tensile strength	f_f	588.2	MPa
Ultimate tensile strain	ε_f	0.027	2.7%
Shear strengthening calculations			
Fully wrapped	n	1	
Mean concrete tensile strength	f_{ctm}	2.96	MPa
Anchorage length	$l_{t,max}$	53.70	mm
Effective strain (0-wrapped)	ε_{fe}	0.004	0.4%
Shear contribution of FRP	V_f	25.7	kN

Standard:	TR55			
Group:	a	Beam nr.	BSa5 and BSa6	
Fibre used:	BAS BI 450			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	202	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	31	MPa
Modulus of elasticity	E_c	27000	MPa
Steel reinforcement			
Steel compressive bars	$Ø_1$	6	mm
Number of compressive bars	K6	2	psc.
Steel compressive reinforcement ratio	ρ_{s1}	0.2	0.2%
Area of compressive reinforcement	A_{s1}	57	mm^2
Steel tensile bars	$Ø_2$	16	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_{s2}	0.013	1.30%
Area of tensile reinforcement	A_{s2}	402	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.45	mm
Width	s_f	400	mm
Number of layers	n	1	-
Fibre alignment	β	45	°
Area of FRP	A_f	360	mm^2
FRP reinforcement ratio	ρ_f	0.012	3.6%
Modulus of elasticity	E_f	25900	MPa
Ultimate tensile strength	f_f	50.3	MPa
Ultimate tensile strain	ε_f	0.007	0.7%
Shear strengthening calculations			
Fully wrapped	n	1	
Mean concrete tensile strength	f_{ctm}	2.96	MPa
Anchorage length	$l_{t,max}$	43.92	mm
Effective strain (0-wrapped)	ε_{fe}	0.004	0.4%
Shear contribution of FRP	V_f	21.6	kN

Standard:	TR55			
Group:	a	Beam nr.	BSa7 and BSa8	
Fibre used:	BAS BI 450			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	202	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	31	MPa
Modulus of elasticity	E_c	27000	MPa
Steel reinforcement			
Steel compressive bars	$Ø_1$	6	mm
Number of compressive bars	K6	2	psc.
Steel compressive reinforcement ratio	ρ_{s1}	0.2	0.2%
Area of compressive reinforcement	A_{s1}	57	mm^2
Steel tensile bars	$Ø_2$	16	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_{s2}	0.013	1.30%
Area of tensile reinforcement	A_{s2}	402	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.45	mm
Width	s_f	400	mm
Number of layers	n	3	-
Fibre alignment	β	45	°
Area of FRP	A_f	1080	mm^2
FRP reinforcement ratio	ρ_f	0.036	3.6%
Modulus of elasticity	E_f	25900	MPa
Ultimate tensile strength	f_f	190.6	MPa
Ultimate tensile strain	ε_f	0.032	3.2%
Shear strengthening calculations			
Fully wrapped	n	1	
Mean concrete tensile strength	f_{ctm}	2.96	Mpa
Anchorage length	$l_{t,max}$	43.92	mm
Effective strain (0-wrapped)	ε_{fe}	0.004	0.4%
Shear contribution of FRP	V_f	74.1	kN

Standard: TR55				
Group: b		Beam nr.	BSb4 and BSb6	
Fibre used: BAS BI 450				
Beam		Notation	Size	Unit
Width		b	150	mm
Height		h	250	mm
Lengt		L	2500	mm
Concrete cover		d_{cover}	40	mm
Effective depth		d	202	mm
Area of concrete		A_c	37500	mm^2
Concrete				
Compressive strength		f_c	30	MPa
Modulus of elasticity		E_c	28000	MPa
Steel reinforcement				
Steel compressive bars		$Ø_1$	6	mm
Number of compressive bars		K6	2	psc.
Steel compressive reinforcement ratio		ρ_{s1}	0.2	0.2%
Area of compressive reinforcement		A_{s1}	57	mm^2
Steel tensile bars		$Ø_2$	16	mm
Number of tensile bars		K16	2	psc.
Steel tensile reinforcement ratio		ρ_{s2}	0.013	1.30%
Area of tensile reinforcement		A_{s2}	402	mm^2
Yield strength		f_y	500	MPa
Modulus of elasticity		E_s	210000	MPa
BFRP external reinforcement				
Thickness		t_f	0.45	mm
Width		s_f	400	mm
Number of layers		n	3	-
Fibre alignment		β	45	°
Area of FRP		A_f	1080	mm^2
FRP reinforcement ratio		ρ_f	0.036	3.6%
Modulus of elasticity		E_f	25900	MPa
Ultimate tensile strength		f_f	190.6	MPa
Ultimate tensile strain		ε_f	0.032	3.2%
Shear strengthening calculations				
Fully wrapped		n	0	
Mean concrete tensile strength		f_{ctm}	2.90	MPa
Anchorage length		$l_{t,max}$	44.40	mm
Effective strain (0-wrapped)		ε_{fe}	0.004	0.4%
Shear contribution of FRP		V_f	79.9	kN

Standard: ACI 440				
Group: c		Beam nr.	BFc3 and BFc8	
Fibre used: BAS UNI 600				
Beam		Notation	Size	Unit
Width		b	150	mm
Height		h	250	mm
Lengt		L	2500	mm
Concrete cover		d_{cover}	40	mm
Effective depth		d	204	mm
Area of concrete		A_c	37500	mm^2
Concrete				
Compressive strength		f_c	56	MPa
Modulus of elasticity		E_c	33000	MPa
Steel reinforcement				
Steel tensile bars		Ø	12	mm
Number of tensile bars		K16	2	psc.
Steel tensile reinforcement ratio		ρ_s	0.0074	0.74%
Area of tensile reinforcement		A_s	226	mm^2
Yield strength		f_y	500	MPa
Modulus of elasticity		E_s	210000	MPa
BFRP external reinforcement				
Thickness		t_f	0.65	mm
Width		s_f	70	mm
length		L_f	2100	mm
Number of layers		n	1	
Area of FRP		A_f	45.5	mm^2
FRP reinforcement ratio		ρ_f	0.0015	0.15%
Modulus of elasticity		E_f	26800	MPa
Ultimate tensile strength		f_f	588.2	MPa
Ultimate tensile strain		ε_f	0.027	2.7%
Flexure strengthening calculations				
Existing strain		ε_{es}	0	0%
Number of layers		n	1	
		nE_ft_f	17420	<180.000
Bond-dependent coefficient		K_m	0.57	
Depth of the neutral axis, ESTIMATED		x_e	40.80	mm
Effective strain in the FRP reinforcement		ε_{fe}	0.015	$<K_m\varepsilon_{fu}$
Strain in the steel reinforcement		ε_s	0.012	1.2%
Stress in the reinforcement		f_s	2520	$f_s>f_y$
Equivalent rectangular stress block		β_1	0.65	
Thickness of the FRP CBM bonding material		t_{CBM}	20	mm
Actual depth of the neutral axis		x	24.1	mm
Flexure load capacity		M	26.9	kNm

Standard:	ACI 440			
Group:	c	Beam nr.	BFc9	
Fibre used:	BAS UNI 600			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	204	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	56	MPa
Modulus of elasticity	E_c	33000	MPa
Steel reinforcement			
Steel tensile bars	Ø	12	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_s	0.0074	0.74%
Area of tensile reinforcement	A_s	226	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.65	mm
Width	s_f	70	mm
Length	L_f	2100	mm
Number of layers	n	1	
Area of FRP	A_f	45.5	mm^2
FRP reinforcement ratio	ρ_f	0.0015	0.15%
Modulus of elasticity	E_f	26800	MPa
Ultimate tensile strength	f_f	588.2	MPa
Ultimate tensile strain	ε_f	0.027	2.7%
Flexure strengthening calculations			
Existing strain	ε_{es}	0	0%
Number of layers	n	1	
	nE_ft_f	17420	<180.000
Bond-dependent coefficient	K_m	0.57	
Depth of the neutral axis, ESTIMATED	x_e	40.80	mm
Effective strain in the FRP reinforcement	ε_{fe}	0.015	$<K_m\varepsilon_{fu}$
Strain in the steel reinforcement	ε_s	0.012	1.2%
Equivalent rectangular stress block	β_1	0.65	
Actual depth of the neutral axis	x	24.1	mm
Flexure load capacity	M	26.7	kNm

Standard:	TR55			
Group:	c	Beam nr.	BFc3 and BFc8	
Fibre used:	BAS UNI 600			

Beam	Notation	Size	Unit
Width	b	150	mm
Height	h	250	mm
Lengt	L	2500	mm
Concrete cover	d_{cover}	40	mm
Effective depth	d	204	mm
Area of concrete	A_c	37500	mm^2
Concrete			
Compressive strength	f_c	56	MPa
Modulus of elasticity	E_c	33000	MPa
Steel reinforcement			
Steel tensile bars	Ø	12	mm
Number of tensile bars	K16	2	psc.
Steel tensile reinforcement ratio	ρ_s	0.0074	0.74%
Area of tensile reinforcement	A_s	226	mm^2
Yield strength	f_y	500	MPa
Modulus of elasticity	E_s	210000	MPa
BFRP external reinforcement			
Thickness	t_f	0.65	mm
Width	s_f	70	mm
length	L_f	2100	mm
Number of layers	n	1	
Area of FRP	A_f	45.5	mm^2
FRP reinforcement ratio	ρ_f	0.0015	0.15%
Modulus of elasticity	E_f	26800	MPa
Ultimate tensile strength	f_f	588.2	MPa
Ultimate tensile strain	ε_f	0.027	2.7%
Flexure strengthening calculations			
Strain in the FRP reinforcement	ε_f	0.008	0.8%
Depth of the neutral axis	x	16.25	mm
Stress level in the steel reinforcement	f_s	1349.4	$f_s>f_y$
Strain in the concrete	ε_c	0.0006	$\varepsilon_c<0.0035$
	z	196.7	mm
Thickness of the FRP CBM bonding material	t_{CBM}	20	mm
Flexure load capacity	M	24.7	kNm

Standard:	TR55			
Group:	c	Beam nr.	BFc9	
Fibre used:	BAS UNI 600			
Beam		Notation	Size	Unit
Width		b	150	mm
Height		h	250	mm
Lengt		L	2500	mm
Concrete cover		d_{cover}	40	mm
Effective depth		d	204	mm
Area of concrete		A_c	37500	mm^2
Concrete				
Compressive strength		f_c	56	MPa
Modulus of elasticity		E_c	33000	MPa
Steel reinforcement				
Steel tensile bars		Ø	12	mm
Number of tensile bars		K16	2	psc.
Steel tensile reinforcement ratio		ρ_s	0.0074	0.74%
Area of tensile reinforcement		A_s	226	mm^2
Yield strength		f_y	500	MPa
Modulus of elasticity		E_s	210000	MPa
BFRP external reinforcement				
Thickness		t_f	0.65	mm
Width		s_f	70	mm
length		L_f	2100	mm
Number of layers		n	1	
Area of FRP		A_f	45.5	mm^2
FRP reinforcement ratio		ρ_f	0.0015	0.15%
Modulus of elasticity		E_f	26800	MPa
Ultimate tensile strength		f_f	588.2	MPa
Ultimate tensile strain		ε_f	0.027	2.7%
Flexure strengthening calculations				
Strain in the FRP reinforcement		ε_f	0.008	0.8%
Depth of the neutral axis		x	16.25	mm
Stress level in the steel reinforcement		f_s	1349.4	$f_s>f_y$
Strain in the concrete		ε_c	0.0006	$\varepsilon_c<0.0035$
		z	196.7	mm
Flexure load capacity		M	24.6	kNm