ADDING EXTRA LOAD BEARING CAPACITY TO REINFORCED CONCRETE BEAMS

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ABSTRACT

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ABSTRACT

The purpose of this thesis was to gather information about the renovation of a concrete structure and strengthening techniques. The aim was to test a reinforced concrete beam at the construction laboratory of HAME. The thesis was commissioned be HAME University of Applied Science. Experiments performed for this survey were done at Sheet Metal Centre under the supervision of its employees and teachers of HAME University of Applied Science.

The first part of the thesis provides general information about reinforced concrete as a structural material. Renovation principles of reinforced concrete and techniques used nowadays are described in this part providing detailed and specified data.

The second part of the thesis focuses on the experiment based on the Hermite process in strengthening of concrete. It discusses the information about the test samples and their manufacture, arrangements and experiments, preliminary calculation and actual values obtained through the test.

The results gained through the experiment are considered a success. They confirm the relevance of the Hermite method and encourage more studies in the field.

Keywords Reinforced concrete, renovation, strengthening, Hermite process, test.

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1 INTRODUCTION

The 20th century was the most groundbreaking period in the world's construction industry. Caused by the population explosion and modern civil technologies it has brought new global standards for the building manufacture.

Since the beginning of the century the Earth population has increased by four times starting from the 1,6 billion people to almost 6 billion people at the end of the century. All of these new citizens are constantly in demand of new places to live, which would be able to fulfil their exponentially growing needs. The majority of the world's exploited buildings were constructed during that time. Since the livings standards and construction technologies have changed each decade, each structure manufactured during that time has its own applicability nowadays.

In the 21st century almost all of previously constructed buildings are still in use. Significant amount of time has passed since their erection, and now we need to renovate them in order to still maintain. Renovation means not only the reparation of old and broken elements, but also the change of the structure to satisfy current needs. Adding extra load bearing capacity is one of them.

It's not always possible to predict the amount of load our structure should sustain, because during the exploitation of a building its original purpose may be changed and additional elements must be added. Reinforced concrete elements are a perfect example. They are the most commonly used parts of structures in civil and industrial construction. Enlarging the load bearing capacities of previously erected concrete structures is a problem faced by the engineers worldwide. Finding of the most optimal way to do it in case of money consumption and quality demand must be an answer.

2 RENOVATION

2.1 General information

Renovation of buildings and structures is a reorganization of them in case of partial or full change in their functional use, implementation of the new more effective equipment, meeting the demands of new standards.

The renovation of buildings consists of redevelopment of premises and enlargement of their height, adding extra load bearing capacity to structures, demolition or replacement of elements, construction of outbuildings and change in the façade. It must be a complex procedure taking into account future redevelopment of a building, factory, or a city district. A lack of view in the future may affect enabling of a possible aftertime renovation without the demolition of the previous one. (Shangin, Bondarenko, Goncharenko & Goncharov 1991, 5-6)

One of the major drivers for the renovation procedure in civil and industrial construction is environmental politics. The implementation of the new environmentally friendly equipment or reduction of the heat and energy consumption may cause significant changes in the overall structure. The higher living standards may also cause a modification of building. Such things as elevator or balcony constructions affect in the recalculation of the load bearing capacities of the whole structure. Also, new safety measures, environment changes, cultural and historical influences, beauty preferences may cause a renovation processes.

The reason to renovate a structure instead of designing a new one is a problem of money. Under the reconstruction and technical redesign of a building budget investments are significantly lower and payback comes two or three times faster than in totally new construction.

In some cases, when it comes to historical heritage these places can't be rebuilt. Some examples are Suomenlinna temple in Helsinki and historical center of St. Petersburg. For these particular reasons, we always use renovation disregarding the financial costs.

Renovation is also a nature of human preferences. For a lot of people it is normal to be a little conservative about their homes. They do not want to move to any other places. Instead they want to live in their family houses or beloved apartments, even if it may seem irrational in terms of money or comfort. (Miettinen, Ripatti & Saarni, 1998, 4-20)

2.2 Different cases for renovation

In each renovation project, plenty of things must be considered. This is because of the specific parameters of each structure and the reasons which have caused their reparation.

Single-family houses can be built from various types of materials: wooden beams, concrete, bricks, glulam timber, air blocks or aerated concrete blocks, prefabricated panels, sandwich walls with metal or wooden framing. The materials are chosen accordingly to fulfil client needs and coincide with the properties of structures.

If we speak about a civil engineering object or multistory houses the most common material is the reinforced concrete. In some special cases, it can be different, for example apartment houses can be built from glulam timber, or prefabricated panels. But when we speak about bridges, warehouses and industrial buildings commonly used materials are concrete and steel due to their high load bearing properties and relatively low prices.

Such important structures as slabs, walls, beams, columns, frames and foundations are made of reinforced concrete. Materials and solutions are chosen depending on the properties of the elements and their damage. Different variations of castings, the addition of internal or external reinforcements, usage of carbon fibers or steel beams, replacement of some parts with newer ones all of these methods are the ways to perform renovation.

The investigation focuses on the field of reinforced concrete due to its high usability. The following chapters provide information about the concrete properties, ways to determine the damage done to construction and chosing a renovation technique and methods to provide higher load-bearing capacities of structural elements.

3 REINFORCED CONCRETE

3.1 PROPERTIES OF CONCRETE

Concrete is a conglomerate made through the solidification of a mixture of water, cement solution, fillers and in extra cases modifying admixtures. The wide choice of fillers and concrete solutions provides different load bearing properties and textural differences. Theories and microstructure models of concrete are overcomplicated due to the heterogeneity of the concrete mass properties.

A high compression strength of concrete is significantly lower than its tensile strength. The addition of steel rods, whose elastic modulus is higher, increases the overall strength, of the structure and makes reinforced concrete. In order to apply the reinforcement concrete must have a high strength, sufficient density and good adhesive properties with steel rods.

The strength of the concrete depends on water proportion, cement properties, surface conditions, outdoor factors, particle sizes, aggregate roughness and adhesion. The stress strain relation in concrete is nonlinear in compression and tension. A generalized curve is linear at small loads and passes extremes at bigger strains.

Thermal expansion of cast concrete is low. It also shrinks as it cures. This may cause various cracks on its structure. The thermal conductivity of concrete is low and it may help to protect the reinforcement from high temperatures in case of fire. However, fire can still deal a significant damage to it at high temperatures.

The shrinkage of the concrete depends on these three factors:

- Lower proportion of cement volume results in a greater shrinkage.
- Higher water-cement ratio (w/s) causes a greater shrinkage.
- Lower particle sizes cause a greater shrinkage.

The microstructure of concrete has a significant impact on its strength and deformation properties. A chemical reaction occurs when cement is mixed with water. A gel consisting of cement particles and various crystalline compounds suspended in water appears. The water to cement ratio is crucial in making perfect concrete. Water excesses reduce concrete strength; a low water content will make the mixture unmixable non-plastic and unable working with it. Concrete can be applied approximately within two hours of being cast. During this time gel develops aggregate particles and solidifies, suspended crystals morph into continuously enlarging crystals. Figure 1 bellow represents differences in structure of concrete^

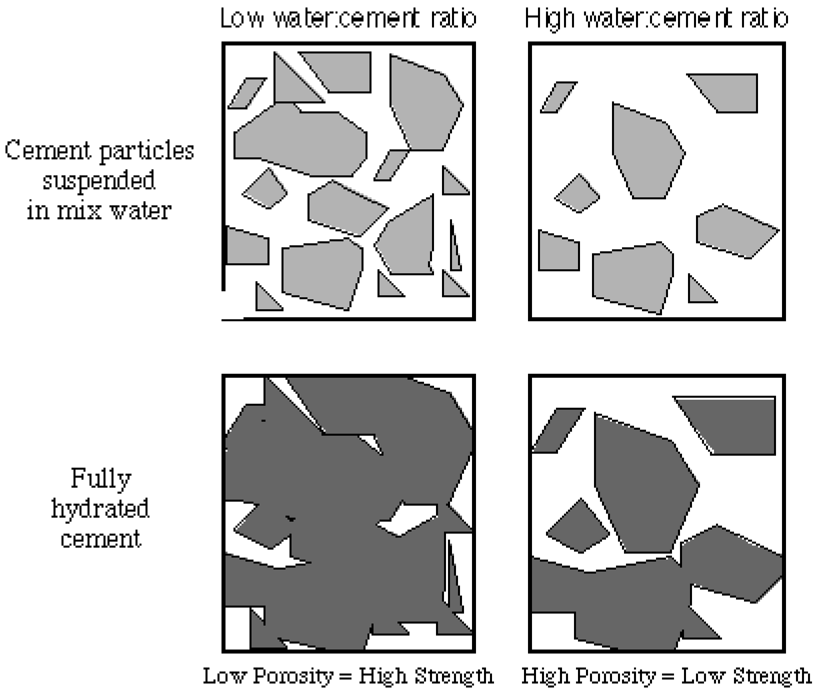

Figure 1. Comparison of a concrete structure.
(http://matse1.matse.illinois.edu/concrete/prin.html)

Solid aggregates take 80% or more of the final microstructure depending on grade. It consists of various calcium compounds, namely, calcium hydroxide, hydro-silicates, hydro-aluminates, and hydro-ferrites. Properties of concrete depend on the extension of its microstructure's porosity and density and the type of porosity.

Concrete microstructure is heterogeneous. It is a capillary-porous material in three basic states: solid, liquid, and gaseous. Thus, the cement stone is heterogeneous, too.

Table 1 bellow represents classification of concrete according to strength in Eurocode. Letter C stands for concrete, first number stands for fck in the cylinder, second number stands for fck in the cube.
(Panasyuk, Marukha & Sylovanyuk, 2014, 30-60)

Table 1. Design strength of concrete.

TABLE TS-5. Design strength (fcm) and the minimum and average strength value requirements for specimens

Concrete Class	Characteristic Strength, fck, (MPa)		Target Strength, fcm (MPa)		
	Cylinder (150x300)	Cube (150x150)	If st. dev. is known	If st. dev. is unknown	
				Cylinder	Cube
C 14/16	14	16	$f_{cm} = f_{ck} + 1.48\sigma$	18	20
C 16/20	16	20		20	24
C 18/22	18	22		22	26
C 20/25	20	25		26	31
C 25/30	25	30		31	36
C 30/37	30	37		36	43
C 35/45	35	45		43	53
C 40/50	40	50		48	58
C 45/55	45	55		53	63
C 50/60	50	60		58	68
C 55/67	55	67		63	75
C 60/75	60	75		68	83
C 70/85	70	85		78	93
C 80/95	80	95		88	103
C 90/105	90	105		98	113
C100/115	100	115		108	123

(http://slideplayer.com/slide/8456316/)

3.2 PROPERTIES OF STEEL

Steel is an alloy of iron and carbon with an addition of other elements. It is widely used in construction because of its high tensile strength and low cost. Taking into account that steel can contain many supplemental elements, it only called steel if the carbon content is between 0.02% to 2.1%.

Carbon gives alloys of iron strength and hardness, reducing the ductility and toughness. The amount of carbon significantly changes the steel structure and it is considered the most important component in consideration of properties. Other alloys can be nickel and chromium, manganese and silicon.

The main advantages of steel usage:

- Enables various architectural designs due to its high load bearing properties and huge variety of forms and shapes of different steel members. The example is the Nest stadium in China.

- Allows to build long spans and high structures due to relatively good added mass/carried load parameters. All of the worldwide constructed skyscrapers use steel as their main structural element.
- Performs with high accuracy when in need of small tolerances and easy installation. This is caused by the prefabrication of the components. It also shortens the erection time on the construction site.
- Recycles easily and can be melted to another structural member at the factory. Recycled steel accounts for 40% of steel produced worldwide, in Finland this ratio is 90%.

The main disadvantages of steel usage:

- Low performance in terms of high temperatures. Steel loses its strength and becomes more ductile. It completely melts at temperatures close to 1400^{o}C.
- Corrosion in contact with air and water. At higher RH level the destruction of outer level comes faster. In order to prevent this various corrosion inhibitors used at already made elements or metals added to steel alloy during manufacture.
- Environmental consequences due to high energy consumption in the steel making process. Carbon oxide, Sulphur oxide, CO_2 and SO_2 emissions are also caused by steel manufacturing. In recent times the development of new ecologically friendly techniques has helped, but they must be improved.

In steel manufacture two different techniques are used and each of them gives steel its own properties:

1. Hot rolled steel. It is a mill process involving rolling of the steel at a high temperature above the steel's recrystallization limit. During such process, steel can be formed into various shapes easily. When the steel will be cooled off it will shrink slightly. This causes less control on the size and shape of the final product comparing to the cold rolled steel.
2. Cold rolled steel. Basically, it is hot rolled steel with further processing. Our material is processed further in cold reduction mills, where it is cooled at a room temperature followed by annealing and temper rolling. This technique will produce steel with closer dimensional tolerances. Cold formed steel provides superior surface treatment, and performs better comparing to hot rolled in terms of tolerance, concentricity, and straightness. Cold finished bars and sheets are typically harder to work with due to the increased carbon content and more expensive than hot rolled steel.

(Havula, 2017)

Table 2 below represents the nominal values of yield an ultimate strength for hot rolled structural steel (fy/fu) according to Eurocode:

Table 2. Steel grades.

Standard and steel grade	Nominal thickness of the element t [mm]			
	t ≤ 40 mm		40 mm < t ≤ 80 mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	510	335	470
S 450	440	550	410	550
EN 10025-3				
S 275 N/NL	275	390	255	370
S 355 N/NL	355	490	335	470
S 420 N/NL	420	520	390	520
S 460 N/NL	460	540	430	540
EN 10025-4				
S 275 M/ML	275	370	255	360
S 355 M/ML	355	470	335	450
S 420 M/ML	420	520	390	500
S 460 M/ML	460	540	430	530
EN 10025-5				
S 235 W	235	360	215	340
S 355 W	355	510	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

(https://moodle.hamk.fi/pluginfile.php/662118/mod_resource/content/1/02_03_Production%20and%20Characteristics%20of%20Steel.pdf)

3.3 PROPERTIES OF REINFORCED CONCRETE

Reinforced concrete is a composite material in which steel is embedded to concrete so that two materials act together in resisting forces. Concrete can perceive only the compression force. It forms the shape of the building structure, provides protection against reinforcement corrosion and serves for fire protection. Steel receives tensile force, increases the compressive and tensile strength of concrete and reduces cracking of concrete elements.

The combination of the two-basic elements has created a significantly beneficial material in following terms:

- Durability - concrete itself in a good environmental condition doesn't need renovation and even increases its compression strength. In this case, it also protects internal steel elements.
- Low cost construction – working at the high loads the creation of the reinforced concrete element will require less steel consumption, which is beneficial to the costs.
- Fire resistance – as was previously mentioned concrete has low thermal conductivity values and creates shelter, protecting steel inside from meltdown.
- Design potential – reinforced concrete structures can be easily made into various forms and shapes. An example of this is Sydney opera.

- High resistance to static and dynamic loads – reached by combining steel and concrete behavior at various types of loads.

On the other side, a major disadvantage of using reinforced concrete is its high mass. On large concrete structures steel is found more effective in terms of added mass/carried load parameters.

Most of the reinforced concrete elements can be divided into two large groups according to their type of loading:

1. Bent elements such as beams, slabs, floor panels etc. Reinforcement made with longitudinal and transvers steel rods. Longitudinal rebar on the bottom is under tension, upper rebar is under compression. Girdle rebar joins all steel structure together and take part of the torsion loads.
2. Compression elements such as columns, pillars etc. The behavior of forces in the compressed element is somewhat reminiscent of the work of bent elements, but in most cases the tensile parts in the element do not occur.

In order to provide good performance of the concrete element the following aspects should be considered at the design and manufacturing stages:

- A strong connection between the concrete and reinforcement must be obtained. It can be the result of adhesion, adhesion due to friction and clutch cut-off resistance.
- Protection of reinforcement from corrosion of the surrounding concrete with a required concrete coverage.
- Compliance of the cement content and water-cement ratio.
- Size of the largest grain referring to the size of the smallest construction members shouldn’t be exceeded.
- The surface of the steel must be cleaned from rust, oil, grease and other contaminants, as well as ice.
- The same thermal expansion of steel and concrete at normal temperatures should be reached.

4 RENOVATION OF REINFORCED CONCRETE

Repair of concrete structures can be carried out at the stage of construction, and during the maintenance process. The renovation process is performed to treat possible fractures and to eliminate defects, which are made during construction or at the erection phase. In the maintenance stage the renovation process is carried out to restore or increase the loadbearing capacity of the structure or to protect it from the damage caused by the environment.

In all cases, the repairs should be completed with high quality to ensure the durability before the next planned renovation procedure. This is only possible to achieve, if we ensure organizational and technical aspects of an issue and make the correct choice of materials and technology work for the repair, taking into account the peculiarities of interactions between repair and repaired materials.

4.1 Damage determination

In order to start the renovation process of the reinforced concrete members and select the correct technique and set of actions, we must first find and determine damages caused to the material. It is essential to be precise and exact in these findings because the development of the renovation program will be based on these observations.

According to the "Repair manual of concrete and reinforced concrete structures of transport facilities in account of materials compatibility (2nd edition)" we can divide various damage types into three certain groups based on the effect on the load bearing capacity:

- In "Group 1" damage practically doesn't reduce the strength or durability of an element, for example: empty spaces; cracks including those caused by shrinkage and accounted into the calculations with an opening not greater than 0.2 mm, as well as those cracks in which under the effect of temporary load and increased temperature disclosure doesn't exceed more than 0.1 mm; chipped concrete and reinforcement without unsheathing etc. These types of damages do not need any urgent actions. They can be eliminated by applying coatings as a protective measure. Therefore, the main purpose of coatings for this group is to stop the development of existing small cracks and prevent the formation of new ones, improve the protective properties of concrete and prevent construction from the atmospheric and chemical corrosion.
- In "Group 2" damage reduces the durability of an element, for example: cracks with corrosion danger greater than 0.2 mm and cracks at the loaded rebar zone greater than 0.1 mm; cracks greater than 0.3 mm at the permanent load; empty shells and spaces with exposed rebar; superficial and deep concrete corrosion, etc. The repair process for the group must provide an increase in the durability of the structure. Therefore, the applicable materials should have sufficient long term actions. The most important part here is to ensure the complete seal of the cracks located at the places of steel reinforcement.
- In "Group 3" damage reduces the load-bearing capacity of an element, for example: cracks not considered at strength and endurance calculations; diagonal cracks of horizontal beams, horizontal cracks at places where a concrete plate is connected to superstructure; large empty spaces and voids at the concrete's

compressed zone; etc. The renovation process for this group is selected based on the damage type and its nature. The materials and technology should provide high strength characteristics and long durability. In most cases, full individual construction projects are needed to repair the damages.

There is also a second kind of damage type division suggested by the “Repair manual of concrete and reinforced concrete structures of transport facilities in account of materials compatibility (2nd edition)” based on damage’s character and classified into five degree groups:

- 1st degree. Dirt on the concrete surface including traces of machine oil, fats, moss or algae; shrinkage cracks; small gaps; slight carbonization without visually observed material drop-off. At the same time concrete’s strength is close to its initial project values.
- 2nd degree. Dilapidated, peeled or cracked surface, drop-offs of small concrete chips. Concrete’s strength is 10% to 15% below design values. Low degree of carbonation, which can be visually spotted.
- 3rd degree. Rust and inactive cracks not greater than 0.2mm on concrete’s surface, chipped concrete. The design values of an element are 15% to 20% below initial project values. High degree of carbonization expressed in the presence of material drop-off areas.
- 4th degree. Active and inactive cracks grater then 0.2mm, numerous chipped concrete, exposed rebar. Concrete’s strength is 20% below design values. Strong degree of carbonization is expressed in presence of products of concrete’s destruction process on the material’s surface, alike stalactites.
- 5th degree. Lose concrete, detached and exposed rebar, hollow sound while hammering the surface indicating the presences of voids. A complete loss of strength values at some parts of an element.

This book also distinguishes three different styles of corrosion of rebar:

- Uniform continuous corrosion in alloys that do not form protective oxide films.
- Intermittent and continuous corrosion taking place in multiphase alloys.
- Local corrosion represented in the form of spots, dots; which is seen in swelling and metal separation with intergranular and selective character.

(Institute of Scientific Research of Transport Construction, 2010, 23-110)

To get a broader view on a problem we can also use the classification from the “Design for reconstruction of buildings and facilities”. This specification also refers to damage type and degree and has five different groups.

1st degree. Concrete is in good condition. Elements meet the requirements for strength, stability, hardness and crack resistance. Durability capabilities are equal to the project's ones. The following factors are satisfied:

- Concrete strength is equal to the design values.
- Concrete surface is clean and free of defects.
- Protective layer of concrete is solid and undamaged.
- While the protective layer of concrete is removed it can be seen that all the rebar is clean and not rusted.
- Corrosion protection of an element is in a good condition.

2nd degree. Concrete is in defective but satisfactory state. It meets the requirements for strength, hardness and fracture toughness. Durability is declined comparing to the project values. The following factors are satisfied:

- Concrete strength is equal to the design values.
- Concrete surface is clean and free of defects causing reduction in strength and toughness. Separate voids and gaps, pores, hairline cracks can be found on a surface.
- A protective layer of concrete is present for half or more of its initial thickness.
- While protective layer of concrete is removed it can be seen that all rebar is clean and not rusted.
- Corrosion protection of an element is in satisfactory condition and mainly not damaged.
- Deflection of an element and the thickness of cracks are within the project values.

3rd degree. Concrete's function is limited, but is still in satisfactory state. It meets the requirements for strength and stability. The durability of an element is significantly reduced. The following factors are satisfied:

- Concrete's strength is equal to the design values.
- Concrete's colour is changed due to dry out.
- Exfoliation of edges as a result of defrosting at the highly saturated condition.
- Rebar is exposed.
- Protective layer of concrete is destroyed for entire thickness at some part of an element.
- Spots of rust can be found on rebar in areas with an insufficient thickness of the protective layer of concrete.
- While the protective layer of concrete is removed it can be seen that rebar has some corrosion in the form of individual dots and spots. Cross-section area of rebar is reduced not greater than 5%.
- Corrosion protection of an element is partly destroyed.
- Crack opening width exceeds the maximum allowed values.
- Deflection of an element does not exceed the maximum permissible value.

4th degree. Concrete is in unsatisfactory state. It doesn't meet the requirements for strength, hardness, stability and durability. The following factors are satisfied:

- Concrete's damage is reducing its strength capabilities. This reduction causes no threat to lives of workers and can't cause an accident.
- The strength of concrete at compression is below the design values for 30% or more.
- There are longitudinal cracks along the rebar at the span. Rebar is rusted. Cross-section area of rebar is reduced greater than 5%.
- Cracks can be found at the compressed zone.
- There are detachments between longitude and shear rebar.
- Deflection of an element exceeds the maximum allowed values more than 30%.

5th degree. Concrete is in pre-emergency and close to failure state. It doesn't meet the requirements for strength, hardness, stability and durability. There is a risk of collapse and the threat to the security of workers. The following factors are satisfied:

- The strength of concrete at compression is below the design values for 40% or more.
- There are longitudinal cracks along the rebar at the span and evidences of rust on rebar. The protective layer of concrete is destroyed for entire thickness.
- Some individual steel rods are broken. Cross-section area of rebar under tension is reduced greater than 50%.
- Surface is contaminated with oil products decreasing the adhesion between rebar and concrete.
- There are cracks grater then 0,5 mm and signs of the compressed zone elements destruction.
- The compressed reinforcement is buckled and concrete is destroyed at compression zones.
- The deflection of horizontal elements is more than 1/50 of the span with an appearance of cracks greater than 0.5 mm at the tension zone.

If during the structures inspection it appears that it is in pre-emergency condition referring to the 5th degree of damage the security measures must be applied at first. Passage of people through such structures must be reorganized, all possible loads must be removed and temporary fasteners must be installed.
(Lazovsky, 2010, 25-48)

The above classifications help us to determine the damage dealt to an element or a structure by its type and its character. A more specified view on different kinds of imperfections, cracks and type of damages is provided in Appendix 1. There you can find examples of various kinds of issues and photos related to each of them.

It is easy to notice that almost always the damage which reduced the technical properties of reinforced concrete is targeting the concrete component at first. The destruction and corrosion of the rebar is a consequence, caused by absences of a good protective layer. Only in cases of an excessive loading both components of reinforced concrete suffer equally and failure occurs at them gradually.

4.2 Common renovation techniques

When we have discovered and observed damages of our structure it's time to choose and implement the right renovation technique. In this chapter, we will broadly discuss the methods used to clean and prepare the surface for future renovation and the possible treatment methods for strongly damaged concrete referring to degrees between 3rd and 5th.

Before we apply any renovation treatment we need to prepare the reinforced concrete and clean it from various contaminants including rust, oil products, dust etc. The methods upon which cleaning is based depends on the contamination type, damage type and material to use in the reparation process. Engineers distinguish four main ways to perform the cleaning:

- Mechanical treatment is made with the use of grinders, cutters, mechanical drills, hammers, pickaxes, sand and shot blasting machines. The instrument selection depends on the amount of the material which needs to be removed. This method is highly recommended in all cases with all types of damages. Only in particular situations where dust can cause problems this solution is not recommended.
- Thermal treatment is made with the use of acetylene-oxygen torches, while concrete is heated not higher then 90^{0}C. This method is used to clean from resins, oil, rubber or organic components. The depth of contamination shouldn't exceed 5mm. After an application of this method mechanical or hydraulic treatment is also needed.
- Hydraulic treatment is made with the use of water jets applying a pressure between 12 to 18 MPa or 60 to 120 MPa. This method is also highly recommended in all cases where presence of water on the construction site and change in air humidity is acceptable.
- Chemical treatment is made with the use of hydrochloric or phosphoric acids. This method is only used where mechanical treatment is not allowed. After an application of this method the surface must be washed with water.

At least one of the methods listed above is used during every renovation operation and even in those situations where we only do regular maintenance of a structure such as an application of paint or polish.

In cases where the element is highly damaged, old and defective material must be removed and then replaced. The new protective layer for rebar is made with freshly cast concrete. An additional layer of concrete and extra rebar is added in case where the necessity of extra load bearing capacity of an element has been considered.

The area of defective concrete and which is in need of removal can be spotted by one of the following signs:

- Surface concrete cover along the reinforcing bars is less than required.
- Concrete is contaminated with products of corrosion from the rebar.
- Concrete has a structural damage represented in multiple cracks, gaps, voids etc.

The place of the steel reinforcement is determined with equipment for rebar search and protective layer measuring. Also, it can be done visually if steel reinforcement is exposed. Then areas to be removed are marked to be sure not to damage rebar during the process.

Concrete is being cut in two phases. At first it is done roughly with the use of jackhammers and then for the high accuracy with electric perforators and non-electric tools. The amount of empty space around the rebar should be equal to its diameter, but not less than 2 cm. The rebar is cleaned with brushes or with chemicals, when the thickness of rust layer is low. If the rust has contaminated more than 30% of a rebar it must be changed.

Figure 2. Removal of concrete.

Figure 3. Removal of concrete.

(Institute of Scientific Research of Transport Construction)

When the excavating procedure of concrete has been finished, the surface must be cleaned and made rough for better adhesion with the new concrete. All the corrosion inhibitors and other protective chemicals for the rebar can be applied, but they still need the required amount of time to dry.

After all the preliminary operations have been made, it’s time to cast a new layer of concrete. If we need extended load bearing capacities for our element, we can add an additional rebar and cast an extra layer of concrete. In this case, we don't use any kinds of mechanical bonds or adhesives because it will enlarge our work. It's easier to implement this method of extra reinforcing than others because we already have a need of casting an additional concrete coating. Other possible ways to improve strength capacities will be discussed in the following chapters.

While casting concrete two separate methods of its implementation are always considered i.e. with and without timbering. It depends on the amount of work to do and place of an element. If the depth of excavated concrete of a horizontal element doesn't exceed 3cm there is no need to use timbering. In cases of larger castings or vertical or underselling elements timbering must be used. It is usually connected to the initial material with anchors or bolts.

In many ways, the use of timbering may cause difficulties with its implementation due to the position of damaged element. Sometimes a really thick layer must be cast but on a vertical element. In these cases, the use of a concrete gun which blasts the material on a surface is essential. Concrete which is used for these needs usually dries faster and contains lower particles.

After concrete is applied its surface is made smooth and flat with vibration machines and hand tools. The quality of concrete depends on this work. When the material is dry, it is time to paint it or cover with water protective films and gels. It's highly important for the outdoor elements.
(Institute of Scientific Research of Transport Construction, 2010, 187-223)

5 ADDING EXTRA LOAD BEARING CAPACITY

As we have already discussed the renovation of an element doesn't always concern the reparation process. It is obligatory to also prolong the lifespan of structures making it satisfy current needs. In cases where damage dealt to reinforced concrete is insignificant referring to 1st and 2nd degrees there is no need to cast a new layer of concrete. Rather we can apply different techniques which will be more suitable in terms of spent time, money and work power.

One of the greatest examples is the existence of concrete bridges. Nowadays the number of vehicles is increasing day by day. Old structures manufactured tens of years before were not made to withstand such loads but still are in a good condition. Engineers all around the world face the problem of finding an effective and easy to apply way to increase their lifespan.

As we know, reinforced concrete elements can be divided into two groups depending on their position and types of loads acting on them. Studies of compressed elements do not provide a big field for an exploration because the tension part does not exist. And tension is where concrete is the weakest due to its structure. Theories and methods applied to strengthening of bent elements have a lot in common with compressed elements, but only in top parts where they express compression. Consequently, investigations for increasing load bearing capacities of concrete elements are worth studying preferably for bending elements in terms of challenge and obtainment of new data.

5.1 Current methods

Current methods on strengthening of horizontal reinforced concrete elements can be divided into three basic groups depending on the process involved:

- Mechanical method, consists of adjustment of new components, which are preferably made of steel, with the bolts, anchor rods etc. New elements are joined to the existing structure.
- Casting method. A new layer of concrete is cast on top of the old element and new rebar is placed in that layer. Bonds between old and new materials are formed through concrete's abilities for adhesion.
- Hermite method involves the attachment of the new element with the use of glues, preferably epoxy resin. New components can be made of various materials such as steel, plastic, carbon fibre etc.

The following picture in Figure 4 represents each method from the left to the right in order in which they occurred in the text:

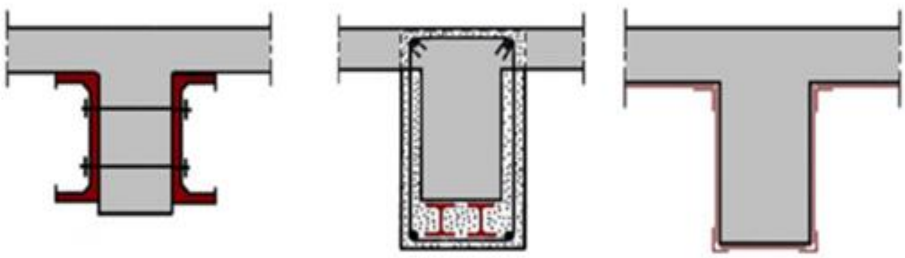

Figure 4. Three basic strengthening methods.
(http://www.constructalia.com/english/renovation_with_steel/iii_beam_reinforcement_techniques#.WDRpL-aLTIX)

Table 3 below is taken from the "Improvement of load bearon capacitis of exisiting bridges". It represents the general relations between different materials in terms of weight, strength and cost. The price is shown in crowns and it's not valid for the due date, but we can still see general proportions in costs.

Table 3. Material comparison.

Material	Modulus of elasticity [GPa]	Compressive strength [MPa]	Tensile strength [MPa]	Density [kg/m³]	Cost [kr/kg]	Relative Cost [kr/m³,(N/m²)]
Concrete	20-40	5-60	1-3	2400	0.2-0.4	1
Steel	200-210	240-690	240-690	7800	3-5	≈3
Carbon fibre*)	200-800	-	2500-7500	1750-1950	100-250	3-4

*) Given values are for plain carbon fibre. The characteristics of the composite will vary with amount and property of the used matrix.

(“Improvement of load bearon capacitis of exisitng bridges”)

5.1.1 Mechanical method

In concrete structures the amount of reinforcement usually determines the strength in tension. When the new material with high stiffness is attached to the tension side of an element it will carry parts of the load in cross section. It doesn’t have to be an internal component. New elements are joined to the original structure through bolts, anchor rods, nails etc. The selection of a supplemental material is wide, but not all of them can suit our needs. We can use wooden or steel plates and metal rods, prefabricated glulam panels etc.

Our choice of supplemental elements depends on the type of load acting on an element and the surrounding environment. In the following, some of their properties are discussed:

- Wood is poor and an impractical solution made in absence of a better material. It is generally weak in terms of strength, it is bad against fire, it decays at high water humidity level and is in need of constant application of various protective paints and gels. The only benefit is a low price.
- Prefabricated glulam panels show better results than simple wood panels, but share the same imperfections and perform poorly at strengthening of horizontal members.
- Steel is most commonly used nowadays. It has good strength properties both in tension and compression. Some alloys can be resistant against rust and have a good performance at high humidity levels, but it increases the price. The prefabrication of steel components allows forms and shapes needed for specific situations. As its weaknesses, it has a bad resistance against fire.

As steel is mainly used for the mechanical method we will consider only it as our supplemental material for the simplicity reasons. In the following some benefits of the mechanical method are listed:

- It can be applied at high humidity levels and low temperatures, whereas the application of hermit and casting methods are unacceptable.

- It doesn't need any adhesion with a repaired element and thus it doesn't need any special surface treatment before application.
- Steel components can be manufactured for each renovation case specifically, which makes it really flexible and allows work in unusual situations requiring unique treatment.
- Steel performs with high efficiency in both tension and compression.
- Elements applied with the mechanical method can be easily removed and reconfigured in case of changing requirements for the structure.

The use of the mechanical method also has some drawbacks, such as:

- Steel can become rusted and lose part of its load bearing capacity. In order to avoid that corrosion inhibitors must be applied or steel special steel alloys must be used. This significantly raises the reparation costs.
- Elements must be connected with a high precision. As bolts and anchor rods are joined to the original element it may cause damage to it if not done carefully.
- There is no protective layer of concrete to cover steel in the mechanical method. It makes the structure vulnerable to fire and excessive heat.

To summarize the facts, we can conclude that the mechanical method is good in certain ways. It can be applied in specific situation and under specific circumstances. To use it broadly special steel protection techniques must be considered. Experiments with different materials can also increase the range of the method's application.

5.1.2 Casting method

The roots of the casting method are old and it was widely used through the whole history of construction. Adding extra material increases the cross-sectional area which inflicts in increment of moment of inertia. The new layer of concrete is casted above the old one. Extra reinforcement can also be embedded to increase the tension resistance.

The benefits of the casting method are the following:

- It can be applied at all damage stages of an element and it doesn't require any specific situations.
- Concrete's layer provides a good protection for internal elements from excessive water content and fire. This results in increased lifespan and durability of a structure.
- It allows the modification in the structure's design: size, forms, shapes.
- Use of steel reinforcement can significantly increase the strength properties of an element.

The use of this methods also has plenty of the drawbacks such as:

- Concrete needs time to dry, while drying the use of the renovated structure must be restricted.
- Surface of an old structure must be carefully treated to provide good adhesion.
- Concrete is influenced by the surrounding environment. It may require special techniques or equipment or cement to apply it under low temperatures and high humidity. In some cases, it may be completely impossible.
- It is hard to apply concrete on vertical and under-roof surface. The use of special blasting devices is required.
- The weight of an element increases significantly affecting the increase of self-load, which causes a decrease in the overall load bearing capacities.

We can see that the use of the casting method has major disadvantages. Despite that it is the main renovation and strengthening techniques right now. It has a long story. People have been using it for decades. It has proved its sustainability. A great number of concrete structures due to high damages can't be fixed in any other manner. What is most important about this method is that it is highly durable and has good long term results.

The absence of scientific research on other methods supports the use of casting method. That is why studies on the new materials and renovation techniques are needed. They can provide new and more effective solutions for the current problems.

5.1.3 Hermite method

The operating principle of the Hermite method is similar to that of the mechanical method. The new material with high stiffness is bounded to tension side of an element it carries parts of the load in cross section; in some cases, it is also true for compression side. The difference is in the specific method with which elements are joined to each other. The use of glue makes separated parts become one unit which can't be easily dismantled. No bolts, nails or any other mechanical fasteners are used here.

The Hermite method has various solutions depending on the type of the glue and glued material. We can roughly divide the supplemental elements into the following groups:

- D-RAP panels are a relatively new form of hermit process application, which have not been studied sufficiently yet. It shows good results in an increase of compression capacities but can't be applied to tension. It's mostly used on top of a road or bridge structures.

- Carbon fibres are a light-weight and flexible material which easily distributes along the surface of a reinforced element. It is not affected by water and can withstand temperatures up to 1600^0C depending on its structure. The major flaw of this material is its high price and inability to increase the compression strength.
- Fibre reinforced plastics or FRP are really close to carbon fibres in terms of their properties. They are more vulnerable to fire and heat, but they can withstand some amount of compression if formed into the right shapes.
- Steel plates are cheapest material among the listed ones. It can take both tension and compression loads, but its fire and water resistance properties are poor.

Glues that can be used are acrylate, polyurethane, epoxy etc. Epoxy is the most common solution due to strong adhesion and high quality technical properties.

The hermit method is beneficial in certain ways such as:

- It is fast to apply. It only takes minutes to put glue on a surface, and no more than half an hour for materials to create strong enough bonds between each other. Than supports holding supplemental elements aren't needed.
- It is flexible. Various types of materials can be used in different cases.
- The increase in strength properties are gigantic, whereas the total weight added is insignificant.
- If supplemental materials and glue are chosen correctly this method can be the cheapest among the all others.

Like all other solutions, the Hermit method also has some disadvantages such as:

- Glue is weak to heat and high air humidity. Various protective films and covers are required for outdoor elements to increase durability.
- Glue is vulnerable to the fatigue loads and their actions must be considered.
- Glue may require certain environmental conditions, which can make its application impossible due to temperature or water vapour content.

In conclusion, it can be stated that the Hermite method was made possible by the recent development of adhesives. Thus, it still has to be studied carefully. Some solutions require more reliable data to step on. Glue industry is continuously developing and introducing aggregates with higher technical properties year by year. Materials like carbon fibres or FPR are also increasing their technical capabilities due to the new manufacture

methods. The flow of new information is far from being over. Plenty of professionals have to work to observe all the incoming data in their construction labs. In this way, the Hermit method has a lot of potential and its performance is yet to be increased.
(Carolin, 1999, 5-27)

6 EXPERIMENT

The use of steel in the Hermite method looks promising. It has good strength properties and a cheap price compared to the other materials. If during tests it proves a substantial increase in load bearing capacities of a reinforced structure it will allow future researches targeting protection from the moisture and heat. Success in these findings may bring cheap and reliable material to use in hermit method to the market.

Valid, up-to-date data is required. That's why we wanted to study this case and shed some light on the problem. The survey in this field can be interesting and important.

6.1 Description of test model

To test the steel, it was decided to manufacture four reinforced concrete beams. These elements are subjected to the point load acting in the middle, causing bending of the beam. The top part will experience compression and bottom part experiences tension.

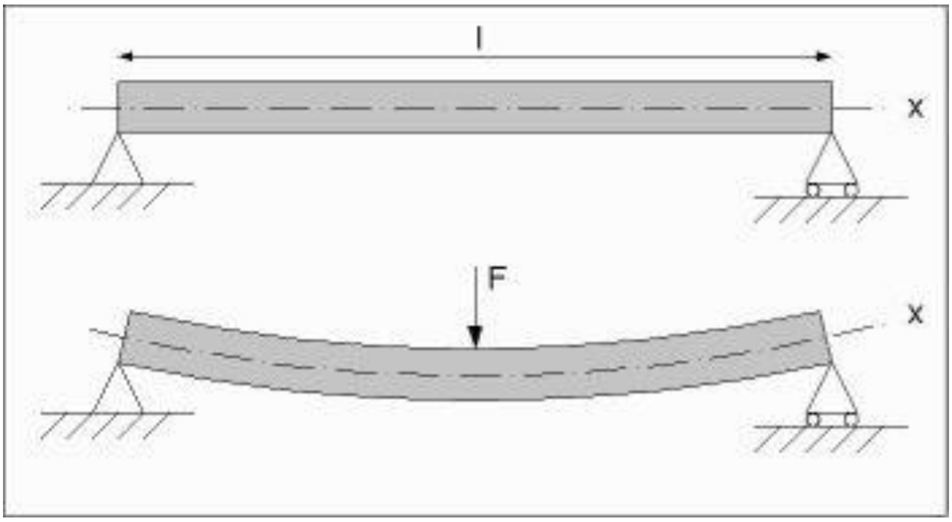

Figure 5. Simply supported beam.
(http://examcrazy.com/Engineering/Mechanical/Lecture-Notes-Beams-Shear-force-bending-moment-diagram.asp)

This loading case can also be described as a simply supported beam (Figure 5). Both edges freely rest on supports (Figures 6, 7). One of them is fixed, another is not. This is done to allow the beam fully bend and not to cause additional resistance from the supports.


Figure 6. Fixed support.

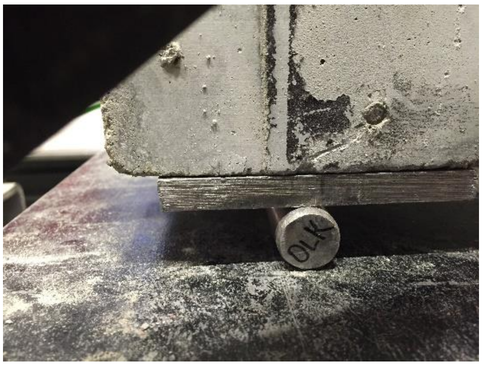

Figure 7. Unfixed support.

The load is applied on a small plate which is situated at the top in the middle of the beam (Figure 8). The plate also rests on the same kind of support as the beams do. It prevents crumbling of the plate due to changes at the top of the beams caused by the compression.

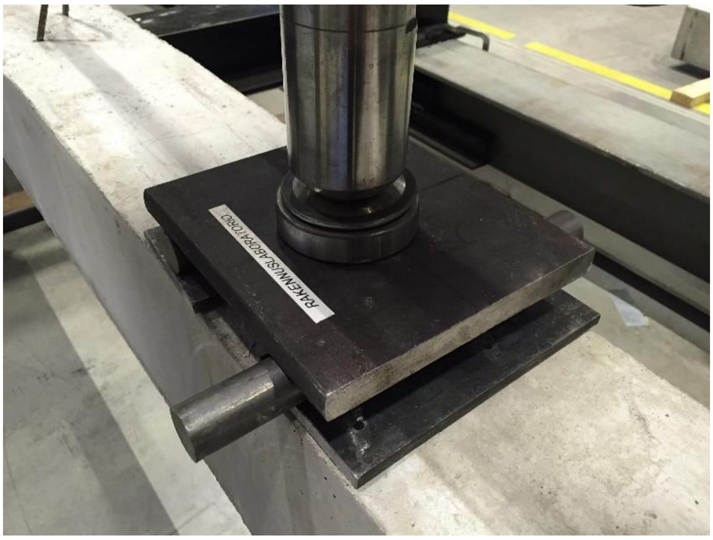
Figure 8. Load application.

Three out of four beams will have a typical amount reinforcement subjected to resist various types of deformation and protect against shear failure, too. One specimen will be designed for testing purposes only, constructed in a way to resist our particular loading case. The behaviour of different beams and the amount of load taken by them should be almost the same. These cases will be studied for the clarity of the experiment and to exclude the possibility of unconsidered behavior. The following drawings (Figures 9-12) represent the exact dimensions of beams and reinforcement.

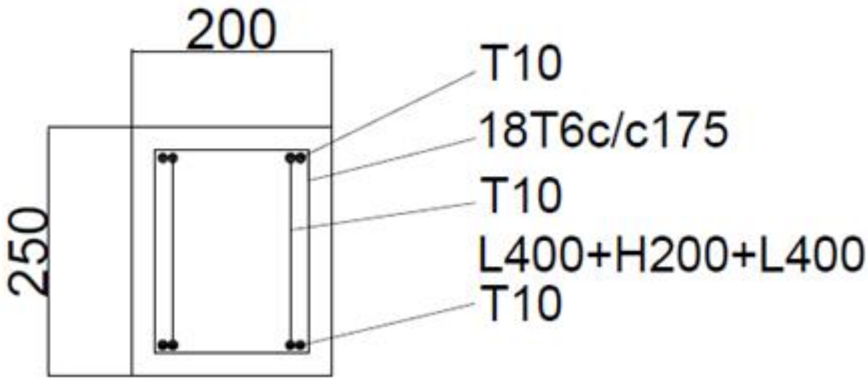

Figure 9. Fully reinforced beam, front view.

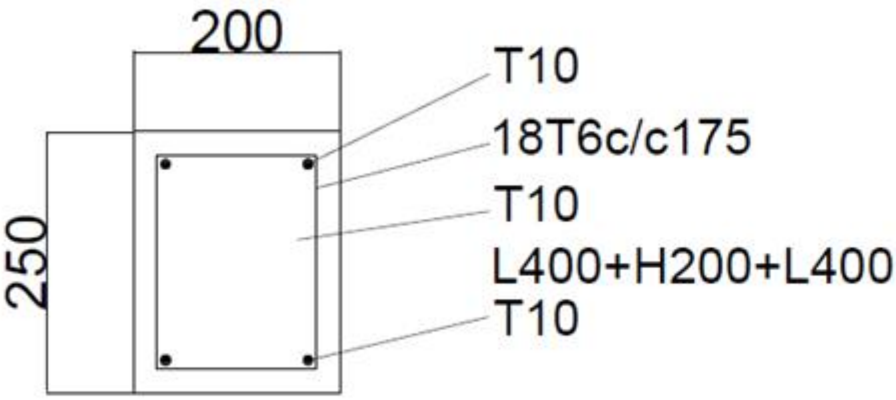

Figure 10. Partially reinforced beam, front view.

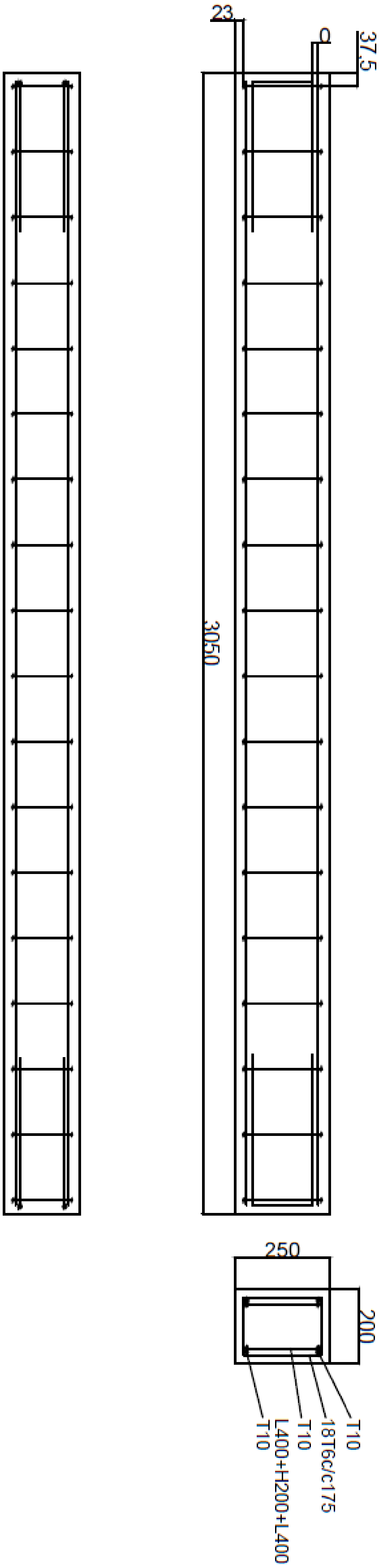

Figure 11. Fully reinforced beam general drawings.

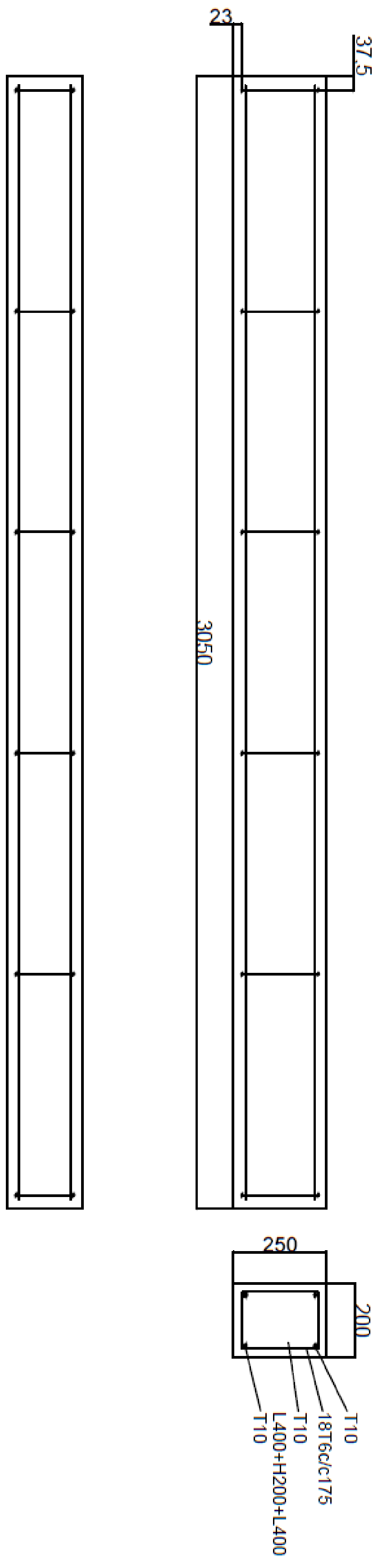

Figure 12. Partially reinforced beam general drawings.

One of the fully reinforced beams will be a control sample. Steel plates are not glued to this specimen. It is done to test the overall quality of beams and reassure that no mistakes were made during the manufacture process. The values to be obtained from this test should correspond to the project values.

The test will be run until the beams are broken or the connection between them and the steel plates is destroyed.

Steel plates will be glued to other three beams. There will be no difference in how they are applied nor in their properties. Each beam will have three steel plates glued on the bottom with 40*2mm^2 in cross section and 2700mm in length. Detailed information on how the plates will be applied is represented in following drawings (Figures 13-16).

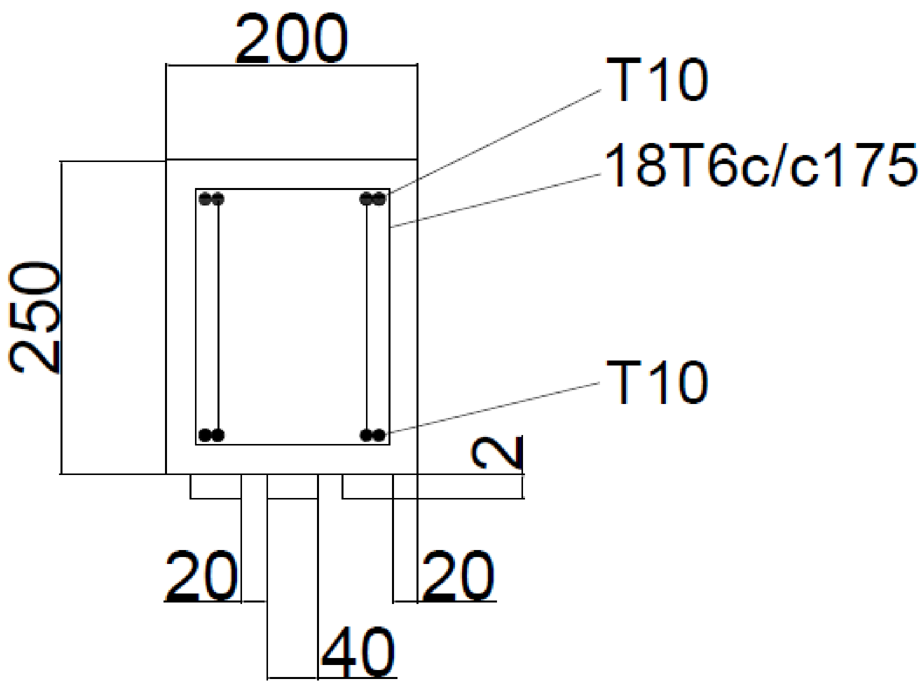

Figure 13. Steel plates application, fully reinforced beam, front view.

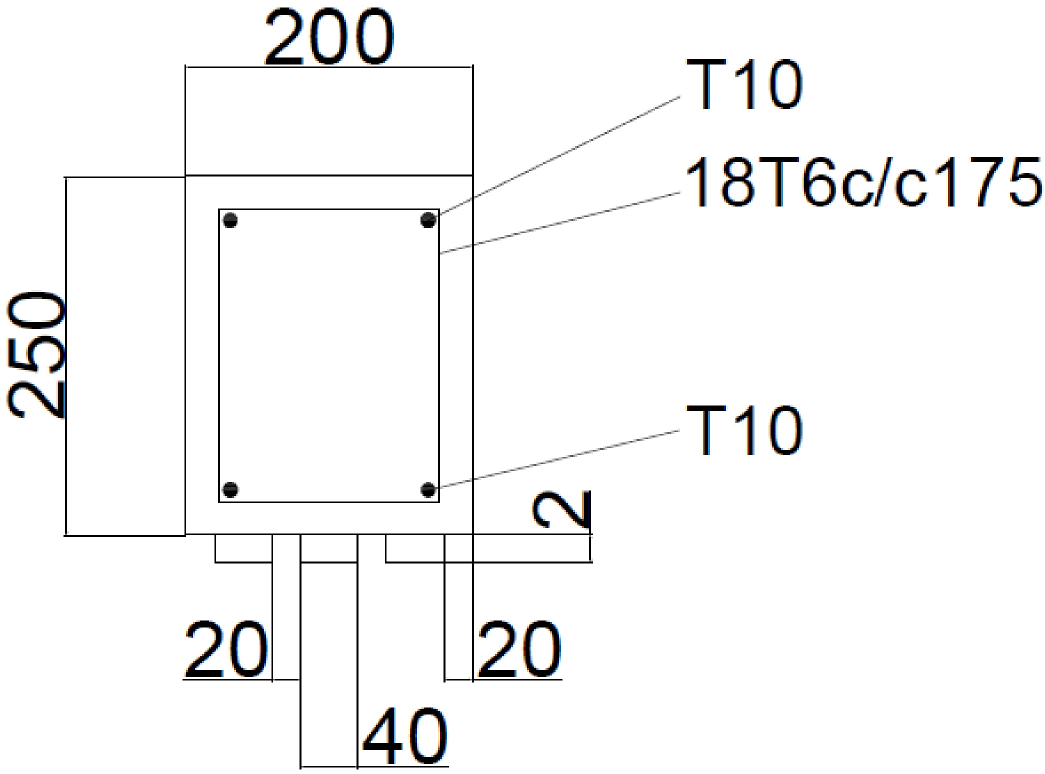

Figure 14. Steel plates application, fully reinforced beam.

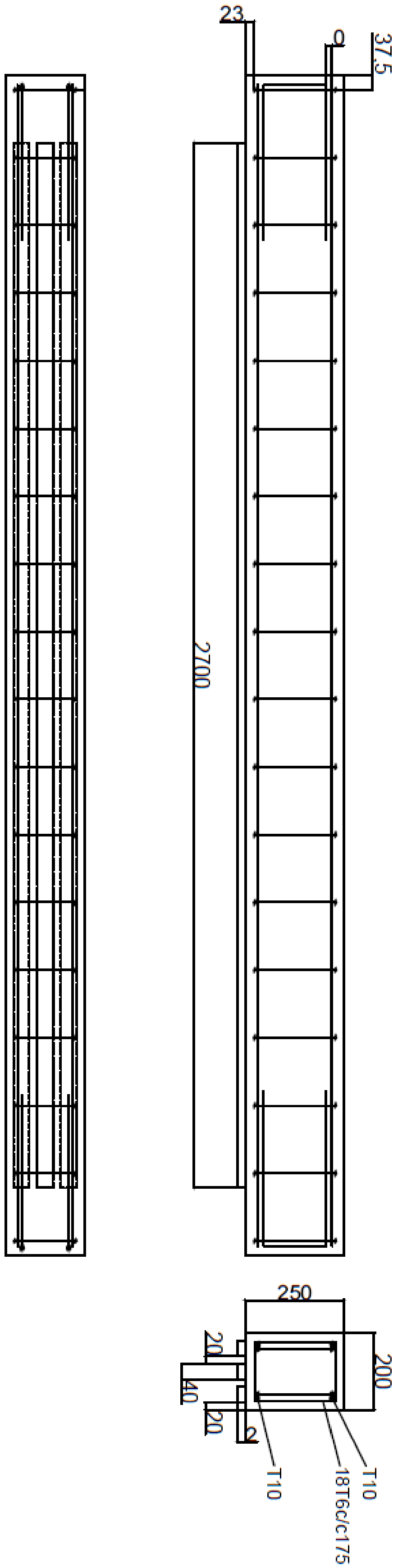

Figure 15. Steel plates application, fully reinforced beam, general drawings.

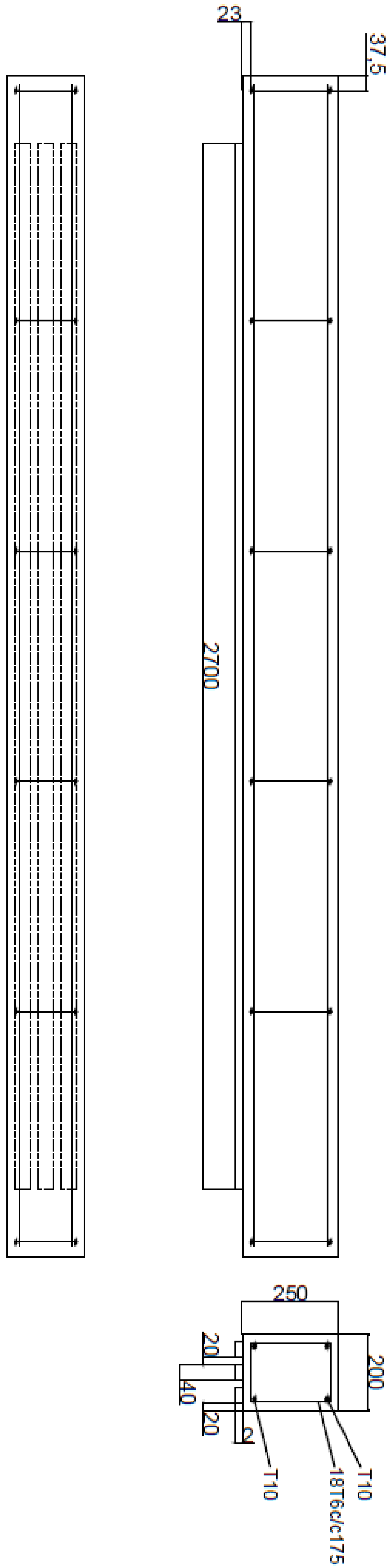

Figure 16. Steel plates application, partially reinforced beam, general drawings.

6.2 **Selection of steel**

When we use flat steel plates their thickness shouldn't exceed an amount of few millimetres. Cross section properties due to the width will be good enough. The application of a thicker element will not make a significant change because a failure is more likely to accrue at the concrete or glue. This is a matter of load bearing capacities of the materials and excessive use of steel will be a waste. Additionally, the application of the bigger weight for the supplemental element may cause the reduction of the glue performance. That is why 2*40 mm^2 cross section is used. The length of steel plates is a 350 mm shorter than the whole beam because the edges rest on supports.

For better adhesion with the glue steel plates with 5mm holes in diameter were selected. When glue comes through these holes, steel area affected by it is increased. These holes reduce the cross section, making the actual value to be 2*30 mm^2 at the thickest part. The plate samples can be seen in Figure 17. The plates are a somewhat bent, because they were distributed in rolls.

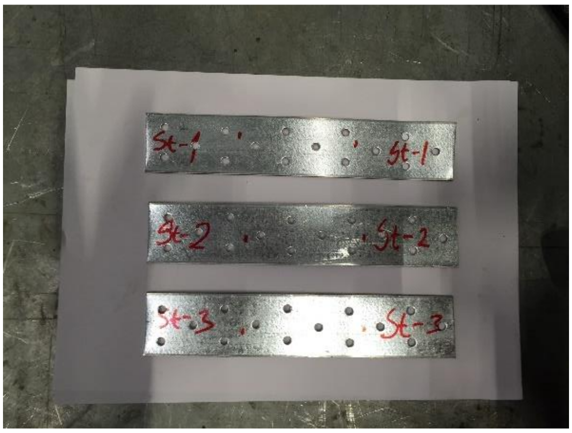

Figure 17. Steel samples from the steel test.

6.3 **Steel test**

To obtain real values of the steel strength it was tested in a tensile test machine. Three different samples with 220mm in length were used (Figure 18). For the ultimate tensile strength 26 KN were taken as an average result of the test.

6.4 **Selection of glue**

Chemical industry is developing rapidly, and many kinds of various adhesives are produced every year. The selection of an appropriate glue is one of the most important choices in the whole survey. It must provide good shear resistance qualities and cause strong bonds between two different materials such as steel and concrete.

HAMK's METNET report from 2015 provides some important data on the use of adhesive at the construction site. The connection resistance of various types of glues under different loading cases is discussed in the report.

One important part there is the test of glue for tension resistance. In our case, glue will experience shear resistance, but we can get the general theme and compare various types of adhesives on their strength properties. Values for the shear resistance of glued connections are lower than the tensile ones and the difference is within 60% to 30%.

The testing was conducted at the tensile test machine (Figure 18), where the thick layer of glue is in between two metal cylinders. The cylinder on the bottom is fixed to the floor, and the cylinder on the top is being pulled up.

Figure 18. Tensile test of a glued connection.

Test results (Table 4) favour the adhesives based on the epoxy resin. They also differ in terms of the thickness of a glue layer, which should stay within 1mm for the best values. It's also mentioned in the report that the connection strength relies on a surface treatment. It must be rough and sandpaper must be applied, otherwise the strength of the connection will be significantly decreased. Based on this data the choice of the Epoxy adhesives was made for our experiment.

Table 4. Test results of a test for glued connection in tension.

Adhesive basis	Parameter [MPa]	Adhesive layer thickness [mm]			
		0,3	1,0	3,0	5,0
Acrylate	$\sigma_{d,A}$	25,44	24,57	20,05	20,29
Polyurethane	$\sigma_{d,A}$	11,94	11,72	7,26	4,09
Epoxy	$\sigma_{d,A}$	35,91	36,62	31,25	23,63

(Ledecky, Ciupack & Pasternak, 2015)

Searching through the web three adhesives which provide the best technical data were selected:

- "Loctite metal to concrete" is especially designed to form strong bonds between metal and concrete materials with an ultimate tensile strength of 22 MPa and ultimate shear strength of 15.8 MPa.
- "T-88 System three" is the strongest adhesive on the market with 48,2 MPa in ultimate tensile strength and 18 MPa in ultimate shear strength.
- "J-B WELD Professional size steel reinforced epoxy" is a good and solid option with 27,3 MPa in ultimate tensile strength.

None of the glues listed above were selected for the test. They require shipping of a few weeks and the price is quite high. The "Plastic Pudding" epoxy was chosen for the experiment. It has 15,7 MPa in ultimate tensile strength and was gladly provided by the SMC. This solution also has good values on paper, but to obtain the best results other glues can be tested. (Ledecky, Ciupack & Pasternak, 2015)

6.5 Glue test

SMC construction laboratory doesn't have a machine for the shear test of the glued connection. Thus, special arrangements are required to get the real value of a glued element.

To solve the problem two separated steel plates are placed in a tensile test machine. Plates are not connected to each other, but each of them is put in front of another and glued to the concrete blocks from both sides (Figure 19). The area of a glue application is 40*70mm at each side. Concrete blocks are resting on the wooden supports and cause no additional load. When plates are torn apart the glue holds them together before the connection is broken. This shows exact values of glue's shear resistance.

Three samples were studied in the experiment. In the first and second cases the steel plates were treated with a sandpaper for better adhesion with concrete blocks. In the third case plates were glued without any special treatment.

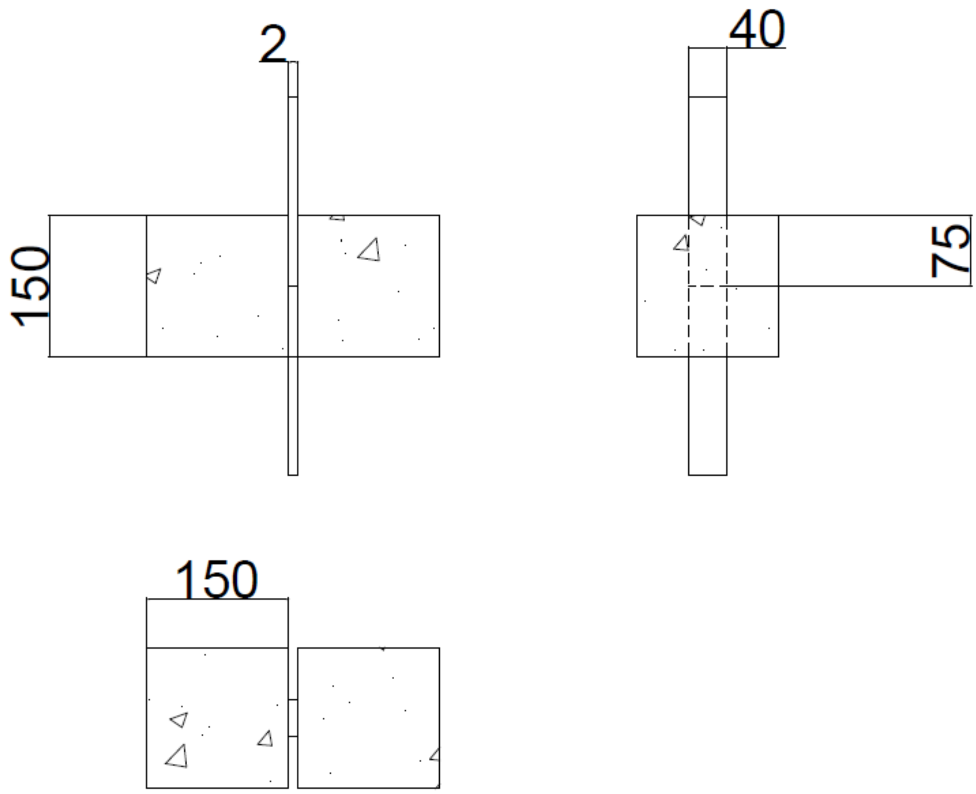

Figure 19. Design of the connection for the shear glue experiment.

The results of the test can be seen in the graphs represented in Figures 20-23 on a following page. Pictures of failure modes and test arrangements can be found in Appendix 2. It was revealed that the sandpaper treatment of the steel plate's surface makes a significant change due to the failure of the third sample. Numbers from the first test were taken for shear resistance of glued connection, because these values are average and are taken from the most representative sample. According to them the connection has failed at the force of 16KN. Using this number the shear resistance of glues was found:

$$\tau = \frac{F}{2A} = \frac{16000\text{N}}{2\times 40\text{mm}\times 70\text{mm}} = 2.857\text{N/mm}^2 \quad (1)$$

In theory, there is no need to apply glue on the whole length of a steel plate. The right amount of glue can be calculated using the following formulas, where the strength of a glued connection is equal to the net-section resistance of a steel plate.

$$\tau \times l \times t = Ns \quad (2)$$

$$l = \frac{Ns}{\tau \times t} = \frac{26000\text{N}}{2.857\text{N/mm}^2\times 40\text{mm}} = 226\text{mm} \quad (3)$$

We apply the glue for the whole length of a sample, because our plates are a little bent and we want to assure a good connection with concrete.

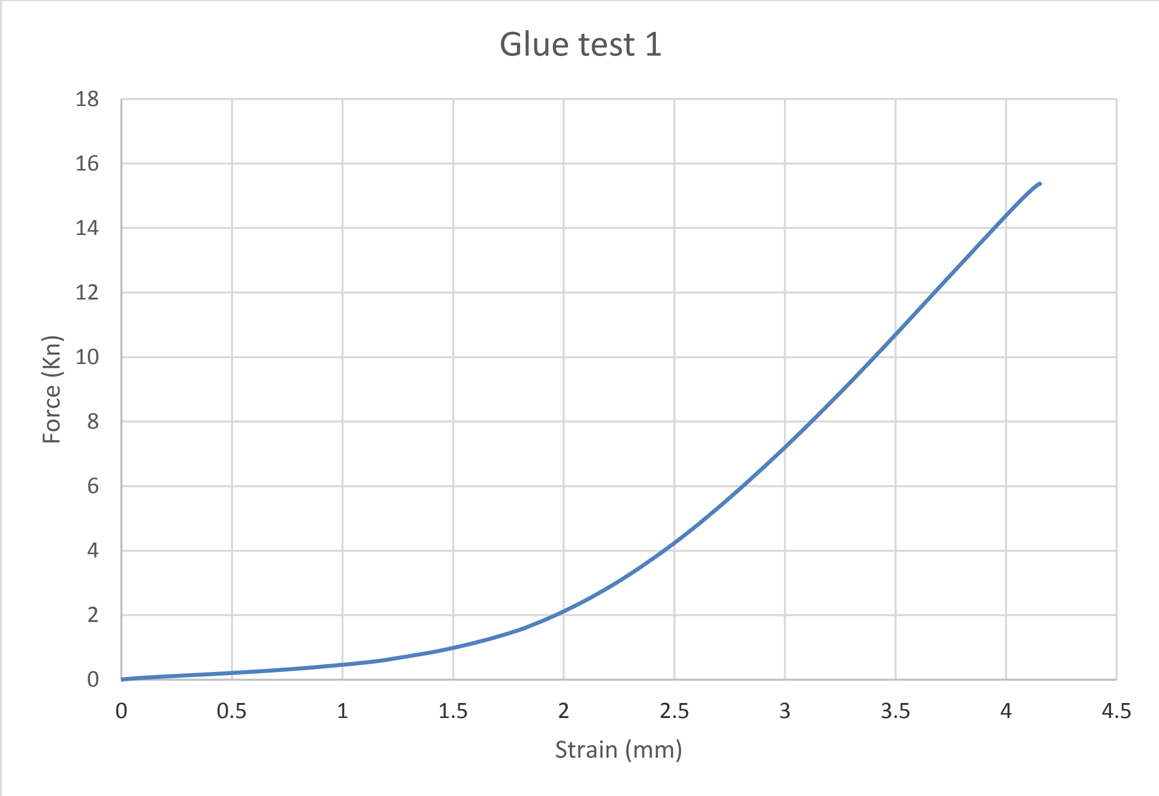

Figure 20. Glue shear test sample 1.

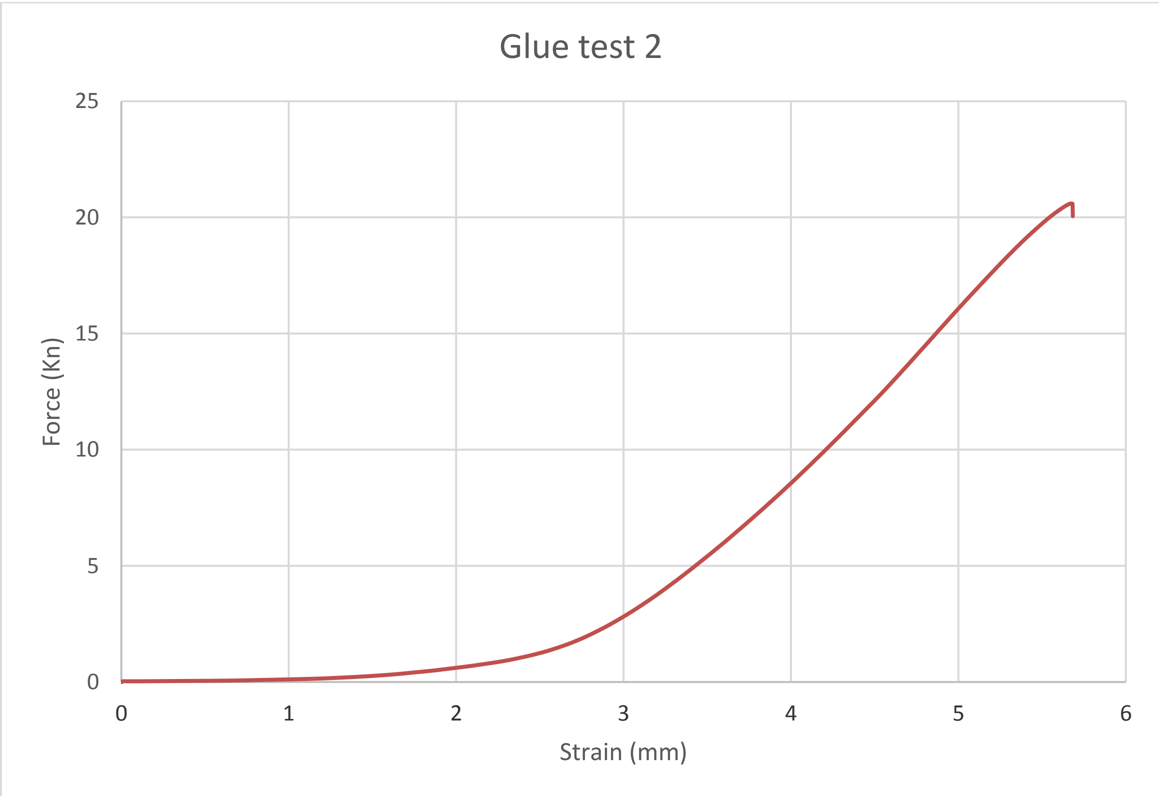

Figure 21. Glue shear test sample 2.

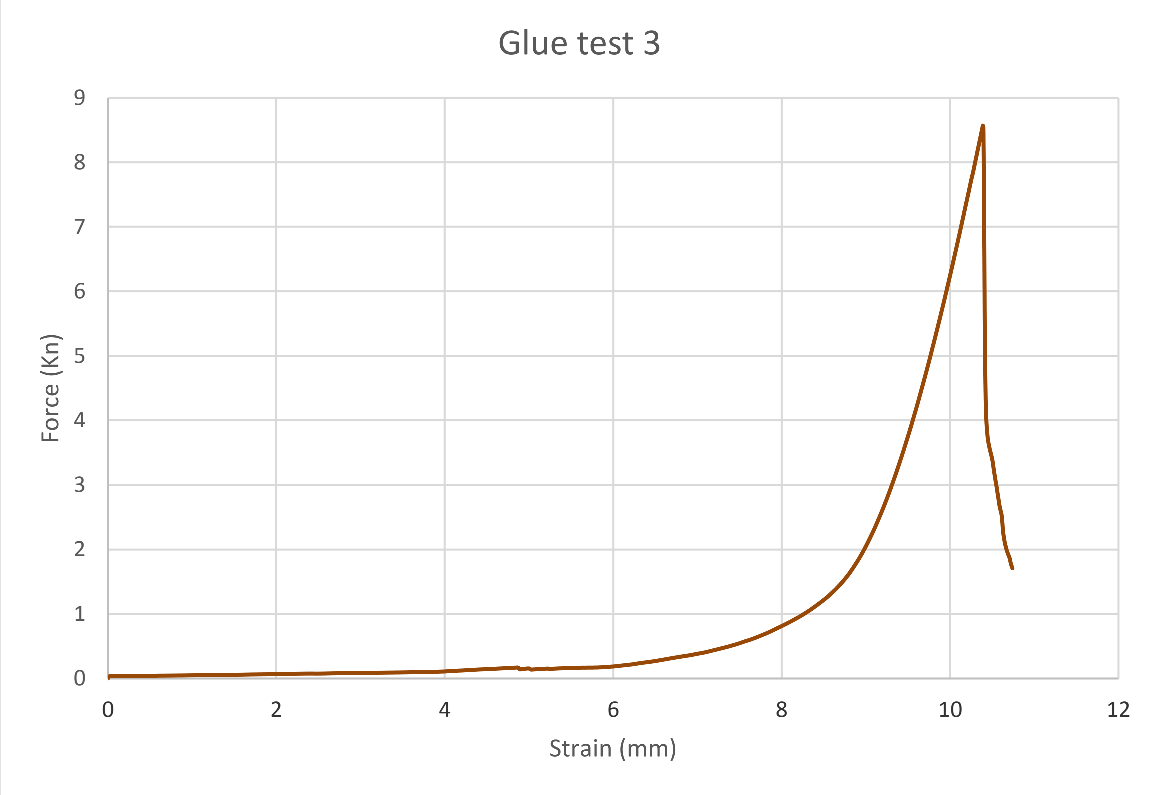

Figure 22. Glue shear test sample 3 / no treatment with sandpaper.

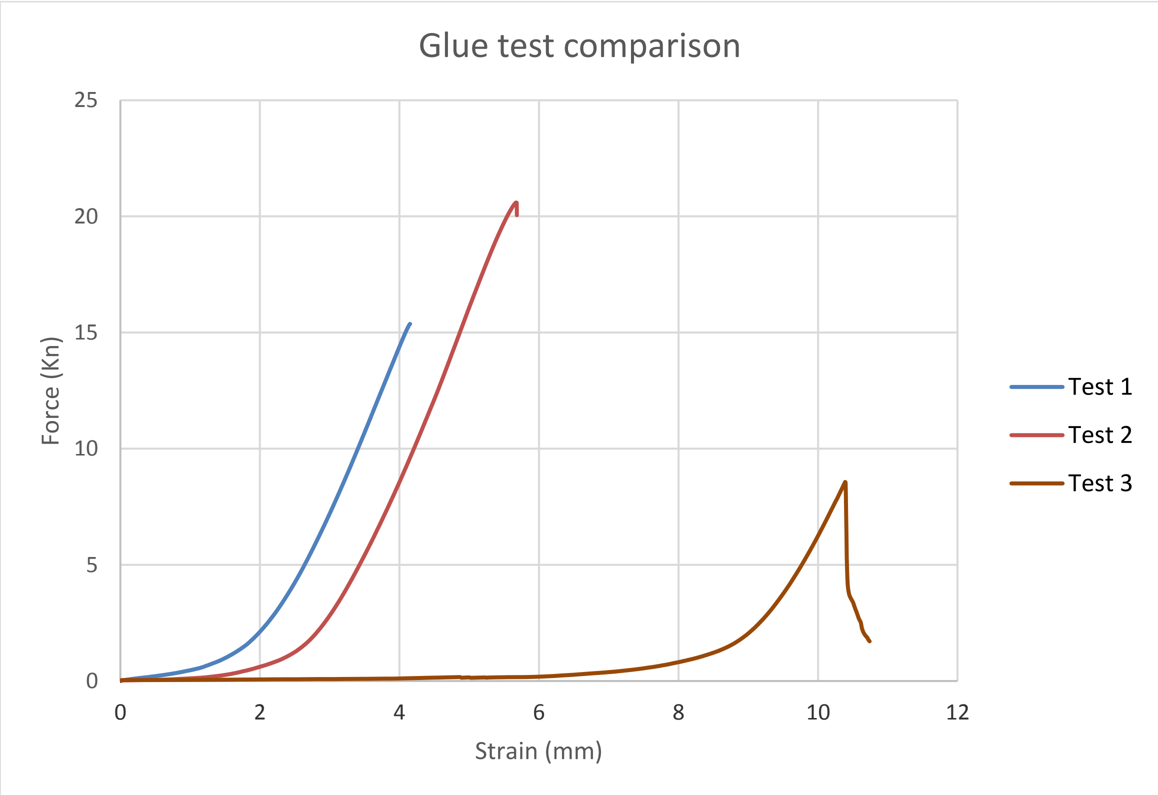

Figure 23. Comparison of glue shear test.

6.6 Manufacture of test specimen

Beams were made at the SMC construction laboratory. Rebars were cut and bent with the use of hand tools, which may slightly have resulted in their load bearing properties. Reinforcement was joined together with the use of wire. Its strength is considered 500 MPa. The steel profile can be seen in Figures 24-25.


Figure 24. Partially reinforced beam. Figure 25. Fully reinforced beam.

Concrete was also cast and applied in the laboratory. To create a substance 11 liters of water were used per every 100kg of cement. The strength properties of concrete are considered 25 MPa. After beams were cast they dried in the laboratory for 28 days.

To apply the glue and bond the metal plates, beams were turned upside down for 180^0. To assure a good connection between steel and concrete an additional pressure of wooden beams tightened with clamps was put from top (Figure 26) while the adhesive was drying. Since glue was applied 20 hours had passed before the experiment. The connection came to its maximum strength during that time.

Figure 26. Glue application.

6.7 **Preliminary calculations**

Before the test preliminary calculations were made to predict the possible outcomes of the survey and explain the future results. These studies were done for both type of beams: fully and partially reinforced, but the formulas and methods used are the same. Thus, values to be obtained are the same. The difference will occur in torsion or shear, but we study our beams only in bending.

The solution below doesn't have any safety factors and represents raw values. This calculation is applicable for the beam failure state. In cases where the beam is subjected to the half of its ultimate load other theories must be applied. In this case, we don't take upper reinforcement into account, because its properties are equal to the reinforcement on the bottom. If it was less, additional parameters would have to be added to the formulas.

6.7.1 Calculations without the steel plates

First, we look at a sample without the plate reinforcement. The strength properties of concrete and steel are mentioned to avoid mistakes:

$$\mathrm{f_{ck}} = 25\mathrm{N/mm^2} \tag{3}$$

$$\mathrm{Nr} = 500\mathrm{N/mm^2} \tag{4}$$

The tensile capacities of concrete are neglectable. It fails as soon as steel rebar fails. Consequently, their ultimate strength equals to the ultimate strength of the reinforcement. The radius of the bottom rebar is 5 mm.

$$\mathrm{Nc} = \mathrm{Nsu} \tag{5}$$

$$Nsu = Nr \times 2 \times \pi r^2 = 500\mathrm{N/mm^2} \times 156\mathrm{mm^2} = 78000\mathrm{N} \tag{6}$$

Figure 27 below represents the force distribution and proportions in the beam used in the following calculations.

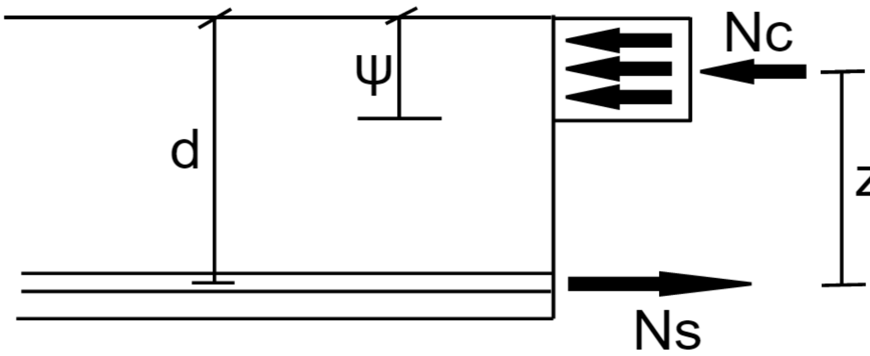

Figure 27. Beam force distribution.

b is the width of the beam. In order to compute z, we find the ψ, which corresponds to the compression zone:

$$Nc = b\psi f_{ck} = Nsu = 78000\text{N} \tag{7}$$

$$\psi = \frac{Nsu}{b \times f_{ck}} = \frac{78000\text{N}}{200\text{mm} \times 25\text{N/mm}^2} = 15.6\text{mm} \tag{8}$$

Only part of the concrete layer above the reinforcement is being under compression. Tension is acting on the rebar. z represents the distance between the force's midpoints. d' stands for the space under rebar.

$$z = d - \frac{\psi}{2} \tag{9}$$

$$d = h - d' = 250\text{mm} - 26\text{mm} - \frac{10}{2}\text{mm} = 219\text{mm} \tag{10}$$

$$\text{z} = 219\text{mm} - \frac{15.6}{2}\text{mm} = 211.2\text{mm} \tag{11}$$

With these values we are able to define the ultimate moment of the beam. Simple formulas from mechanics define this loading case:

$$Mu = Nsu \times \text{z} = \text{Nc} \times \text{z} \tag{12}$$

$$Mu = 78000N \times 211.2\text{mm} = 16.473\text{KNm} \tag{13}$$

$$Mu = \frac{1}{4}FL = 16.473\text{KNm} \tag{14}$$

The span of the beam between two supports is 2,9m. Now we can find the maximum force to be applied on the beam disregarding the self-weight:

$$L = 2.9\text{m} \tag{15}$$

$$F = \frac{4 \times Mu}{L} = \frac{4 \times 16.473KNm}{2.9m} = 22.7KN \tag{16}$$

Now we compute the load caused by self-weight, with the use of an average density of concrete:

$$g = A \times \rho = 0.2 \times 0.25 \times 24\text{KN/mm}^3 d = 1.2\text{KN/m} \tag{17}$$

$$Mg = \frac{1}{8} \times g \times L^2 = \frac{1}{8} \times 1.2\text{KN/m} \times 2.9\text{m}^2 = 1.26\text{KNm} \tag{18}$$

The total load to be applied to the beam with regard to the self-weight:

$$F = \frac{4 \times (Mu - Mg)}{L} = \frac{4 \times (16.473\text{KNm} - 1.26\text{KNm})}{2.9\text{m}} = 20.9\text{KN} \tag{19}$$

6.7.2 Calculations with the steel plates

The calculation process is very much the same as in the previous case. The difference comes from the appearance of an additional reinforcement, and application of an extra force. But this force is acting in the same principle as Ns for rebar. An updated drawing can be found in Figure 28.

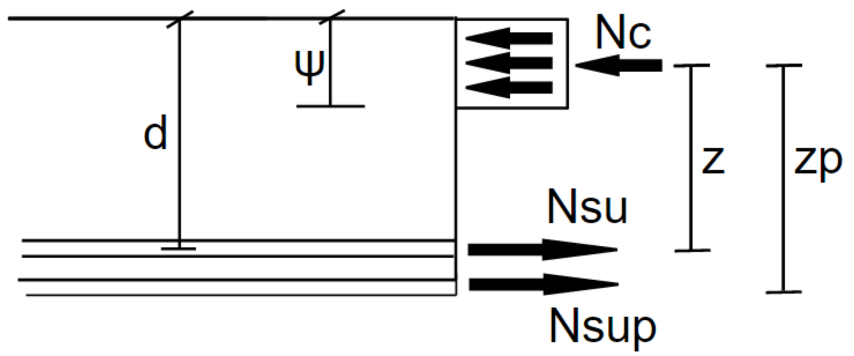

Figure 28. Beam with steel plates force distribution.

We have already found the ultimate tensile resistance of the rebar from the previous case. Now we need ultimate tensile resistance of the steel plates altogether, knowing that one can hold no more than 26KN. This is from the result of our steel test.

$$Nsu = 78\text{KN} \tag{20}$$

$$Nsup = n \times Fu = 3 \times 26\text{KN} = 78\text{KN} \tag{21}$$

An equality of the forces is just a coincidence. Concrete's compression is equal to the tension in both additional reinforcement and rebar:

$$b\psi f_{ck} = Nsu + Nsup \tag{22}$$

$$\psi = \frac{Nsu+Nsup}{b\times f_{ck}} = \frac{78\text{KN}+78\text{KN}}{200\text{mm}\times 25\text{N/mm}^2} = 31.2\text{mm} \tag{23}$$

The values refer to the same parameter as in the previous case. z and z_p represents the distance between the force's midpoints. d' stands for the space under rebar. t_p is the thickness of the steel plates.

$$z = d - \frac{\psi}{2} \tag{24}$$

$$d = h - d' = 250\text{mm} - 26\text{mm} - \frac{10}{2}\text{mm} = 219\text{mm} \tag{25}$$

$$\text{z} = \text{d} - \frac{\psi}{2} = 219\text{mm} - \frac{31.2}{2}\text{mm} = 203.4\text{mm} \tag{26}$$

$$t_p = 2\text{mm} \tag{27}$$

$$z_p = z + d' + \frac{t_p}{2} = 219\text{mm} + \frac{2\text{mm}}{2} = 235.4\text{mm} \qquad (28)$$

Now we are able to calculate the ultimate moment. We use the same simple formulas from mechanics:

$$Mu = Nsu \times \text{z} + \text{Nsup} \times z_p = 78\text{KN} \times 211.2\text{mm} + 78\text{KN} \times 235.4\text{mm} = 34.2\text{KNm} (29)$$

$$Mu = \frac{1}{4}FL = 34.2\text{KNm} \qquad (30)$$

We can calculate the ultimate force disregarding the self-weight:

$$F = \frac{4 \times Mu}{L} = \frac{4 \times 34.2KNm}{2.9m} = 47.2KN \qquad (31)$$

For the self-weight calculations, we use the same parameters of the density of concrete:

$$g = A \times \rho = 0.2 \times 0.25 \times 24\text{KN/mm}^3 d = 1.2\text{KN/m} \qquad (32)$$

$$Mg = \frac{1}{8} \times g \times L^2 = \frac{1}{8} \times 1.2\text{KN/m} \times 2.9\text{m}^2 = 1.26\text{KNm} \qquad (33)$$

The final formula allows us to find the maximum force to be applied to the beam with regard to the self-weight:

$$F = \frac{4 \times (Mu - Mg)}{L} = \frac{4 \times (34.2\text{KNm} - 1.26\text{KNm})}{2.9\text{m}} = 45.4\text{KN} \qquad (34)$$

Values we have obtained promise the increase in load bearing capacities for 125%. For more precise and detailed information we need to perform the testing.

6.8 Beam test

Here is a reminder of the test samples from the experiment:

- Control sample, which is a fully reinforced beam without bonding of the steel plates. The diagram with the results is represented in the Figure 29.
- Beam 1, which is a fully reinforced beam with bonding of the steel plates. The diagram with the results is represented in the Figure 30.
- Beam 2, which is a fully reinforced beam with bonding of the steel plates. The diagram with the results is represented in the Figure 31.
- Weak, which is a partially reinforced beam with bonding of the steel plates. The diagram with the results is represented in the Figure 32.

The comparison of the results is represented in the diagram in Figure 34.

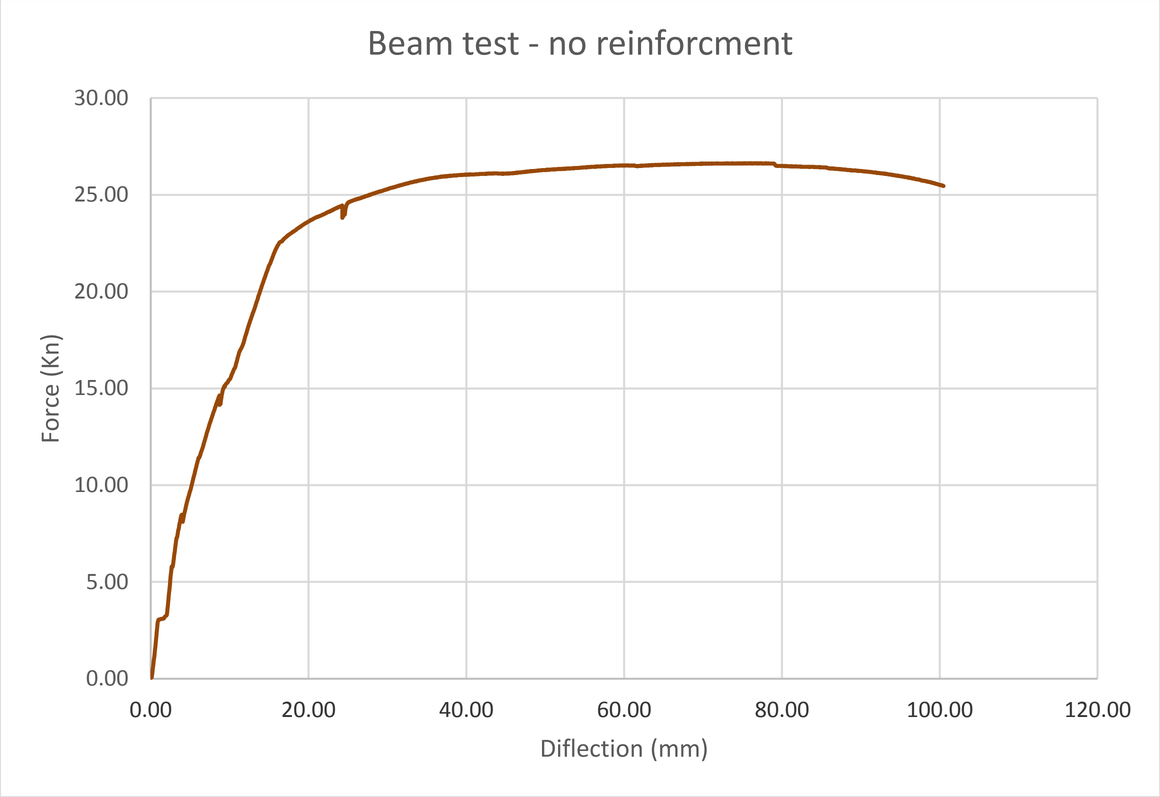

Figure 29. Beam test, control sample.

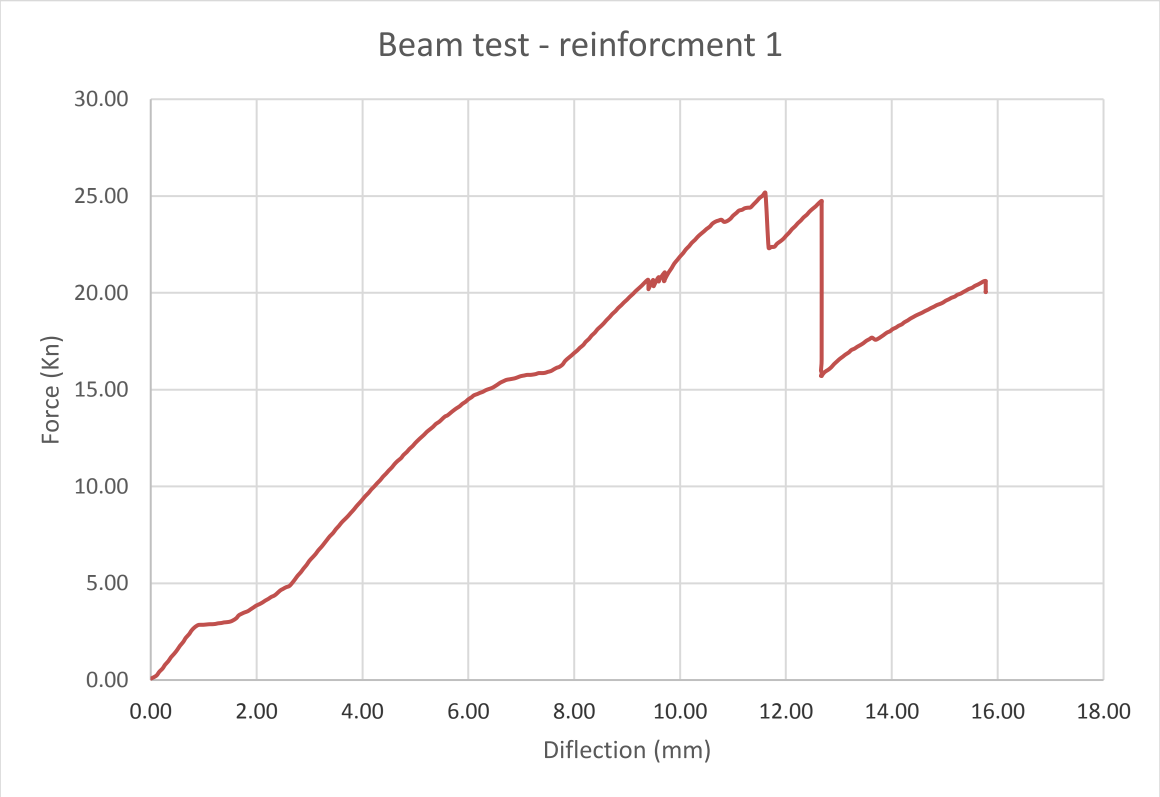

Figure 30. Beam test, fully reinforced beam 1.

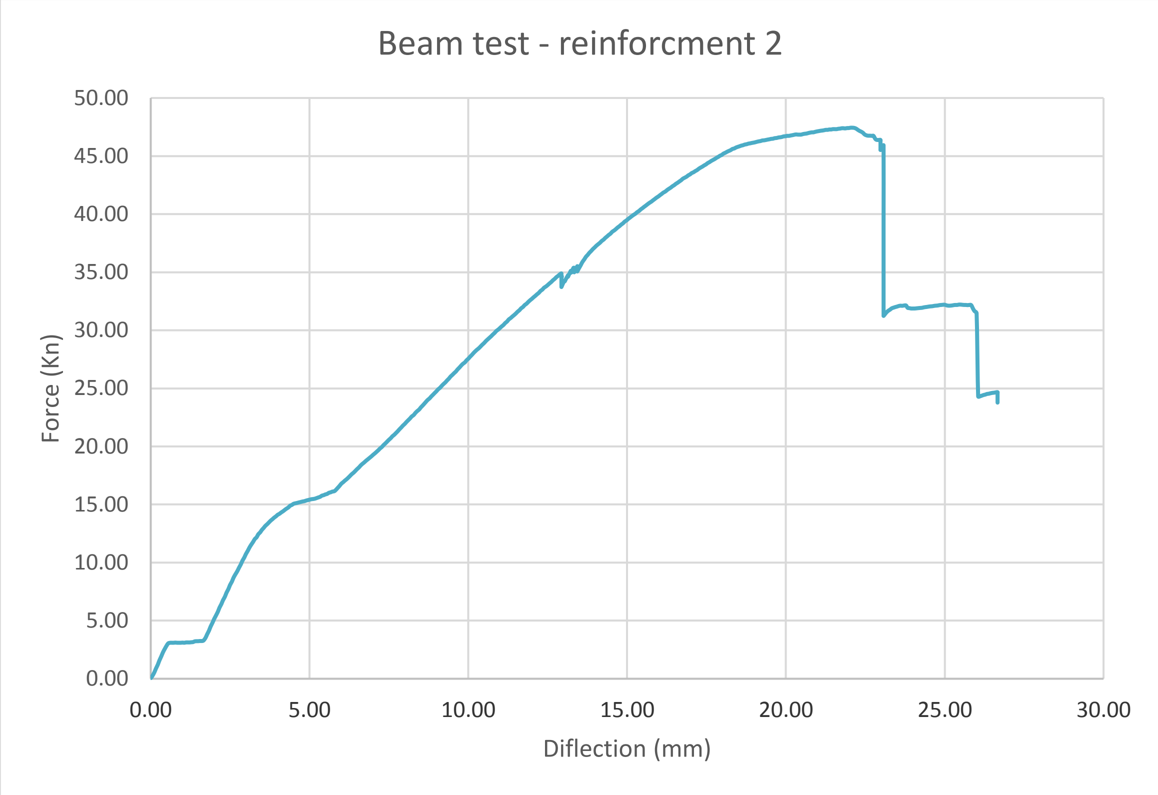

Figure 31. Beam test, fully reinforced beam 2.

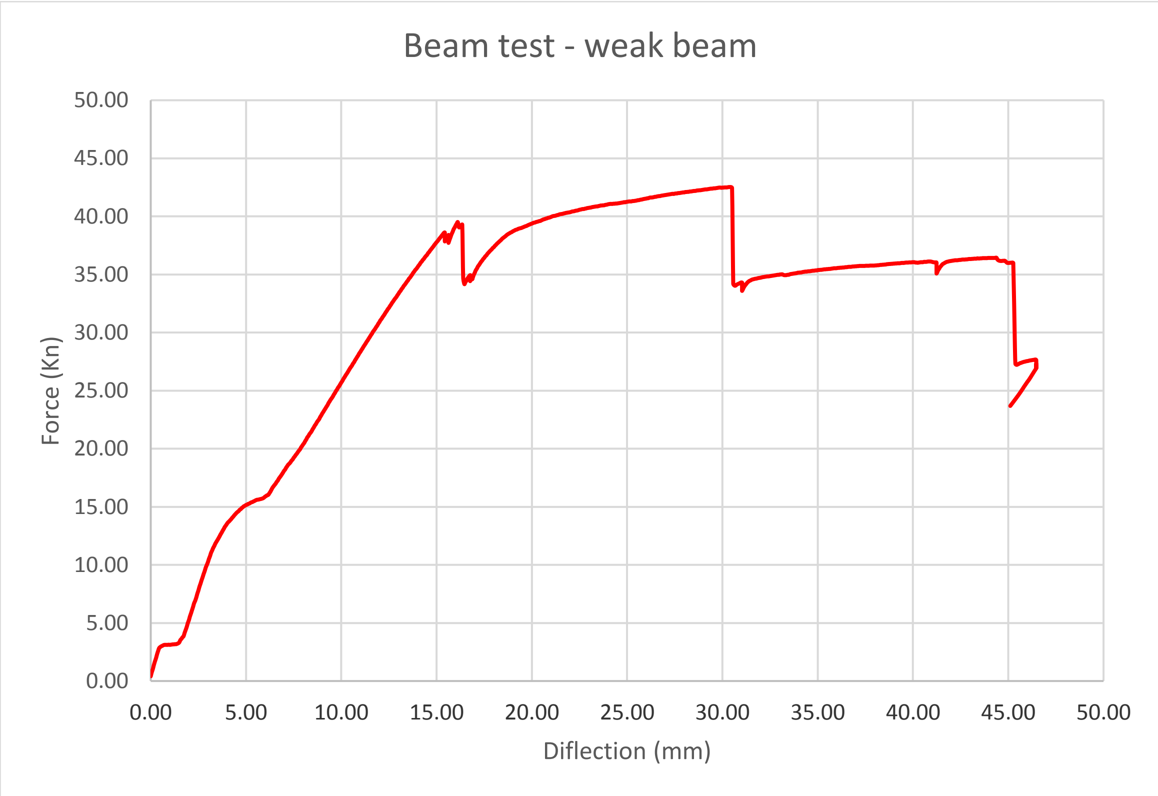

Figure 32. Beam test, partially reinforced beam 2.

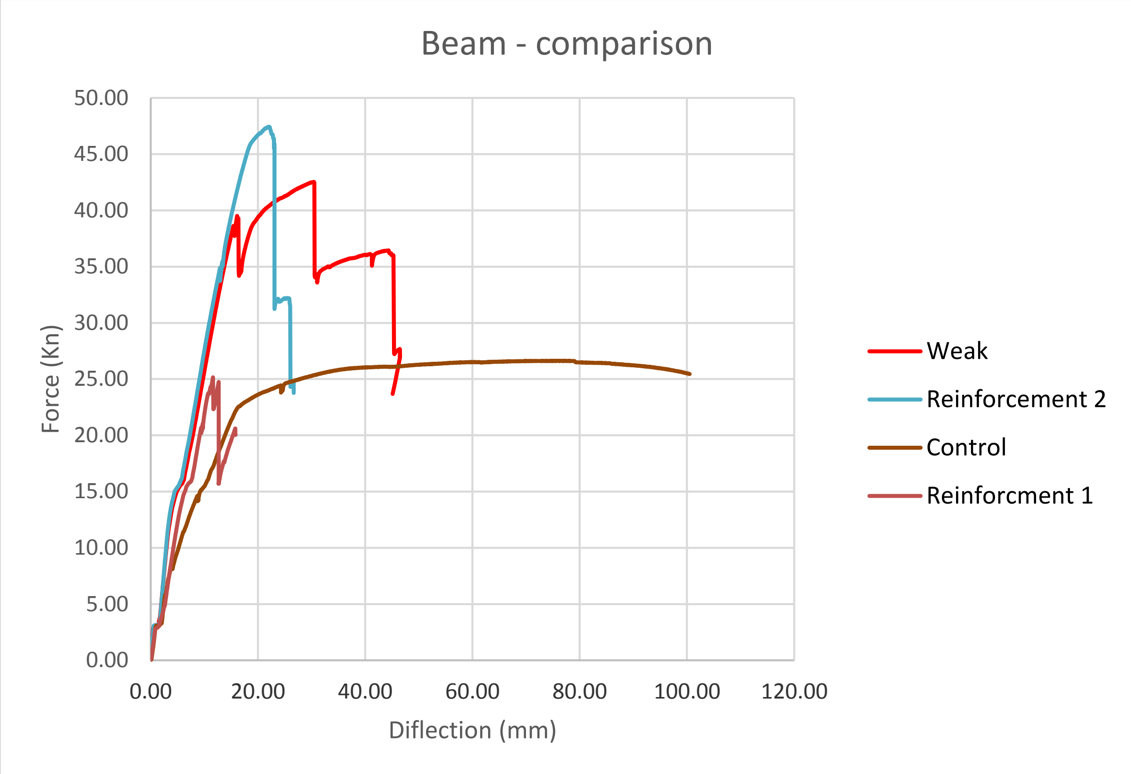

Figure 33. Comparison of the beam tests.

In the graphs corresponding to the test sample with the glued steel plates three peaks can be seen. At best, it is represented at the first and partially reinforced beams. These peaks stand for the failure of the steel plates. The graph was going down, at each time one of them lost the connection with the beam.

As you can see the values for the control beam has shown an increase in 5 KN comparing with an estimated amount. The reason for this is the tensile strength of rebar. The manufacturer to be on the safe side always tells the lowest possible capabilities for their products. It allowed the tensile strength of the reinforcement exceed the expected amount, which has caused the mistake.

The failure of the first beam at the same amount of load happened due to wrong glue application. Probably, too much glue was applied and the surface of concrete was greasy. This plus small bending of steel plates may have caused poor results. Now we can't be certain on the exact reasons.

The third beam has exceeded an estimated amount for 3KN. The failure accrued in the glue, and may be caused by slight imperfections at the adhesive application.

The fourth beam broke 2KN less then estimated value and a failure was caused by both glue and concrete. These results are the reason for a higher tensile strength of rebar. Perhaps, with a better glue application the failure would occur only in concrete and at a higher load.

The load bearing capacity increase for the two last attempts is 73% and can be considered a success.

When we are discussing about the beams one of the most important parameters is a deflection. When it reaches maximum, the cracks are starting to appear on the concrete's surface. Maximum allowed deflection can be calculated as follows:

$$D_a = \frac{L}{250} = \frac{3050mm}{250} = 12{,}2\ mm \tag{35}$$

The following Table 5 represents the loads corresponding to and allowed deflection, and the deflection corresponding to the maximum load:

Table 5. Deflection values

	Allowed values		Maximum values	
Beam sample	Deflection	Force	Deflection	Force(Max)
Control	*12,2 mm*	*18 KN*	*40mm*	*25.9 KN*
Fully R 1	*12,2 mm*	*25,1KN*	*12,2 mm*	*25.1KN*
Fully R 2	*12,2 mm*	*32KN*	*23 mm*	*48.4KN*
Partially R	*12,2 mm*	*27 KN*	*30,5mm*	*43.4 KN*

As we can see the average increase for the third and fourth case was 63% in load for the maximum allowed deflection. This is a more reliable added value because it stays within the safety measures.

6.9 **Conclusion of the test**

The performance of the manufactured samples can be considered a success. They have shown a significant increase in load bearing capacities for more than 50%. The failure happened due to the glue in all the three cases. We know that there are better solutions for the adhesive selection. Their testing at the same arrangements of beams and reinforcement is needed to explore the true load bearing properties of this type of connection. The failure of a concrete layer will show that shear capabilities of the glue has reached the maximum strength required for the strongest type of connection, then the exact maximum possible strengthening can be determined.

Also, for the future tests the following additional experiments can be considered:

- Tensile tests where reinforcement is glued on the edges. This loading case and combined load application can bring some more knowledge for real structures where the beam is experiencing various kinds of loads.
- Long term tests where the lifespan of a glued connection can be determined. This is one of the most important data to obtain because durability qualities have an influence on the overall pricing of a method.
- Tests where glued connection on beams is being under fatigue or cyclic loads caused by vibrations. This is a case for industrial buildings because they experience a lot of vibration.
- Tests with different kinds of supplemental material. Perhaps aluminium or other metals can be selected. They should differ only in load bearing properties, but clear evidence is needed. New materials can perform better than steel in certain environmental conditions.

- Tests of the heat and water influence on glue and a supplemental material. These are the parts of a durability test and one of the most required for safety measures for the long use of an element.
- Tests on pre-cracked elements with a noticeable damage are required to understand the application of the method for higher damages degrees of reinforced concrete.

The results of the beam test have proven the consistence of the method and prepared the ground for future findings.

7 CONCLUSION

The renovation of concrete is a long and difficult process. The necessity in this procedure appeared only few decades ago and the best way to do it is still to be discovered. The rapid growth in creation of new tools for the construction sector and related spheres only extends the field for the investigations.

Hermite methods can be a solution which is cheap and fast. Current trends do not support the use of glued connection without an additional mechanical fastening, but this can soon be over. We encourage more people to test and provide scientific researches for the development of the construction sector.

Our test has once again proved the validity of the method, but the scope of a survey wasn't sufficient to provide significant information. However, not only the Hermite method is interesting for the experimenters, studies of highly damaged concrete are most conservative part according to technologies used. Thus, even more reliable information has to be obtained.

The 21st century is a time, when the ecology is endangering, and in order to save it we have to learn how to maintain rather than stick to something new. Curiosity in the field of renovation can help in reaching this noble goal.

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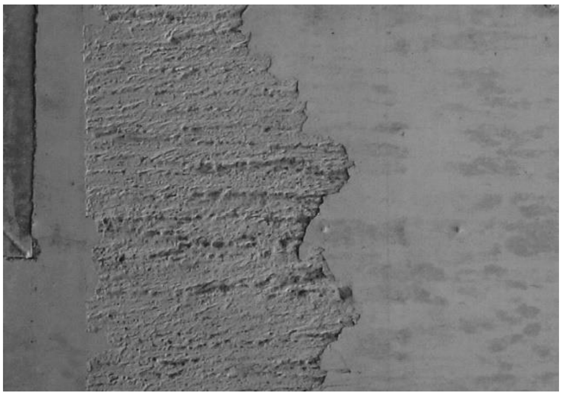
Appendix 1/3 (page 1)

Types of concrete's damages

Exposed rebar



Destruction of the protective layer of a wall surface

Lack of vibration

Cracks due to the shrinkage

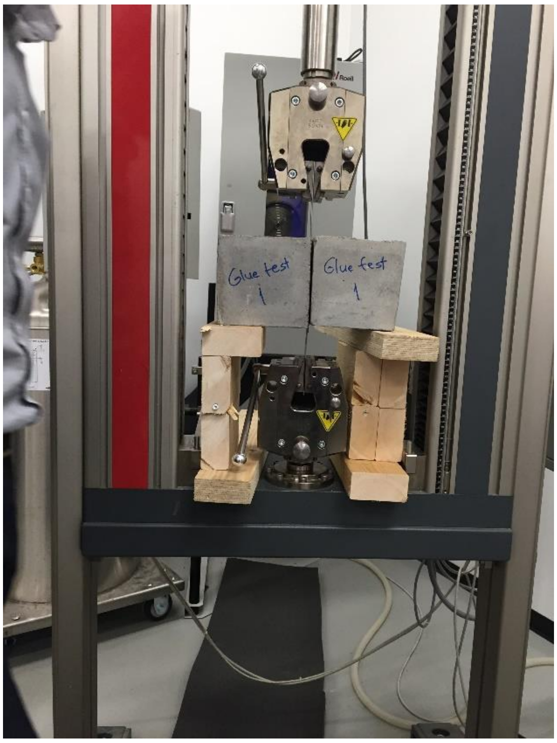
Inappropriate use of steel rod's fixation

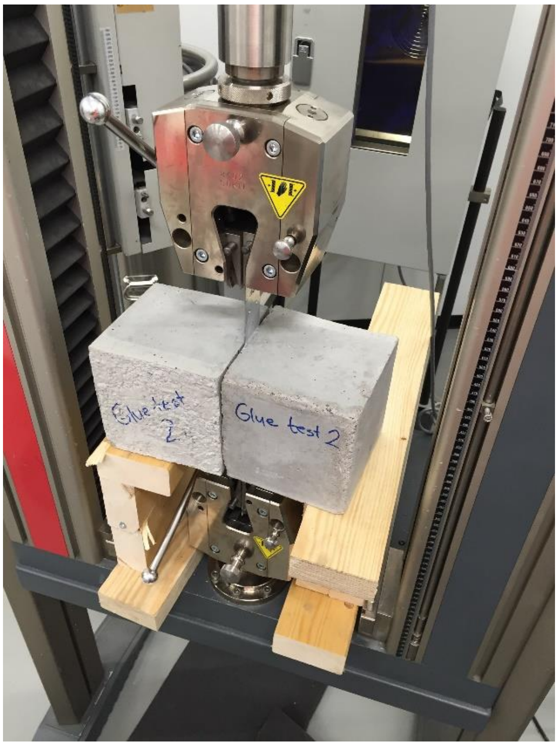
Corroded and exposed rebar

Concrete covered in mold

Appendix 2/3 (page 1)

Photos of the glue test





Glue test arrangements

First sample failure mode

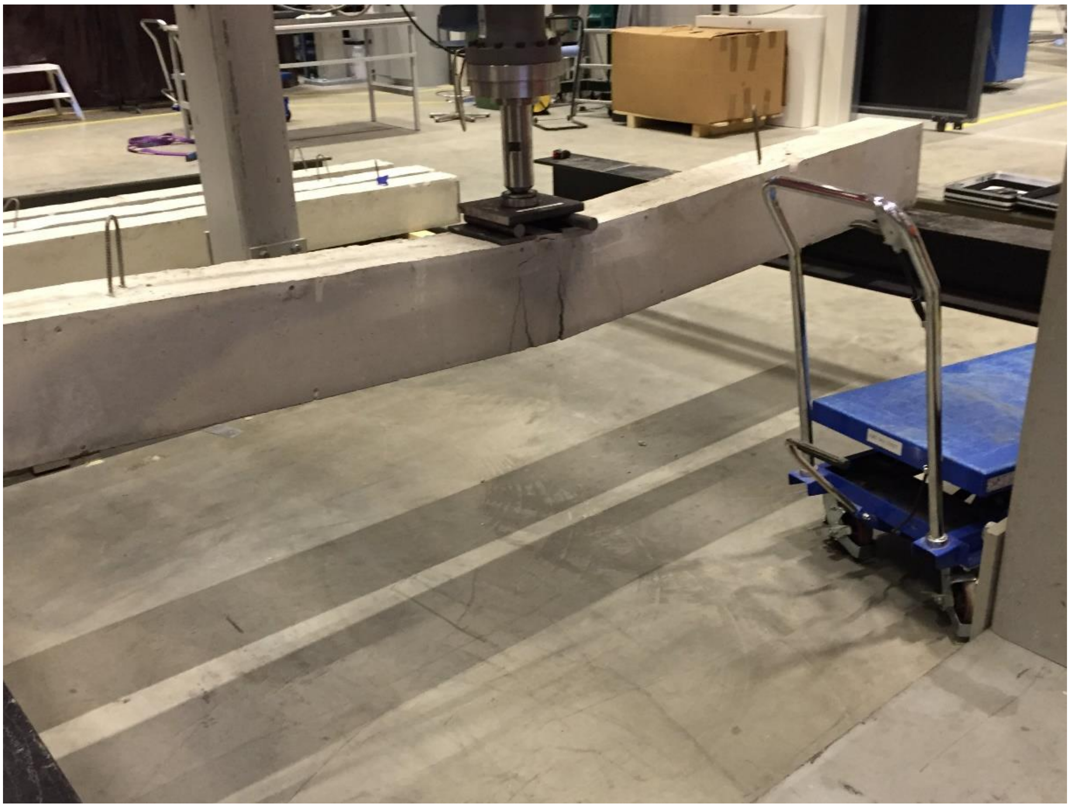
Photos of the glue test

Second sample failure mode

Third sample failure mode

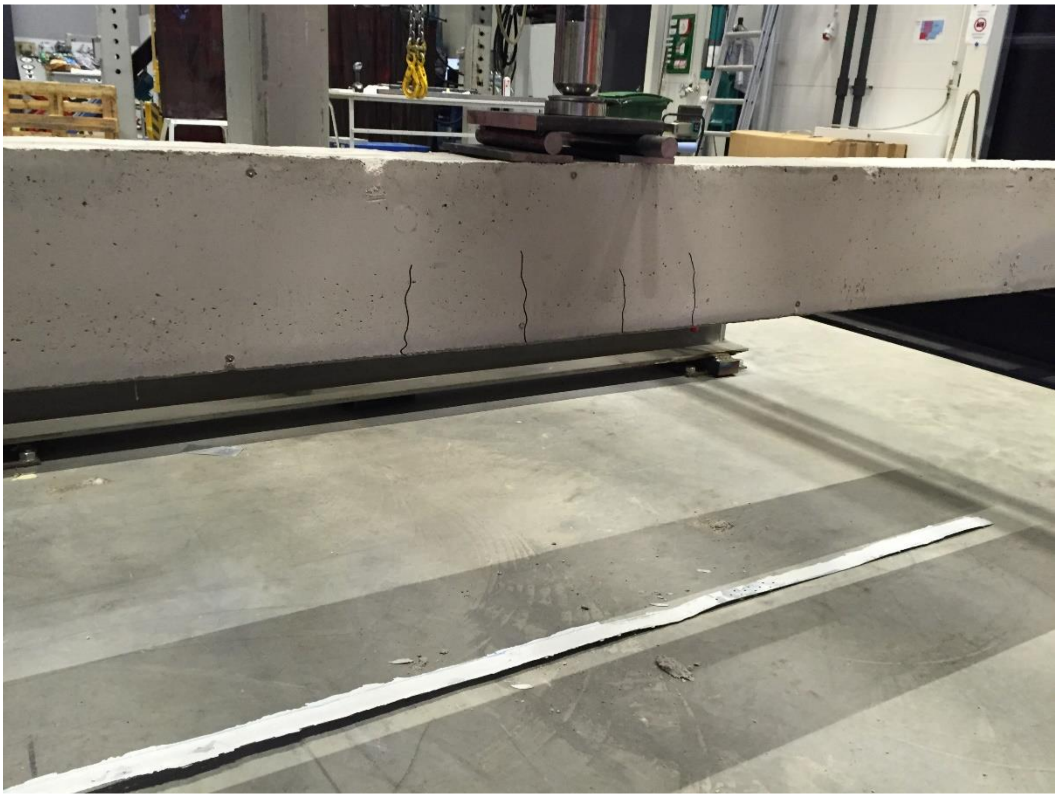
Photos of the Beam test

Glued steel plates

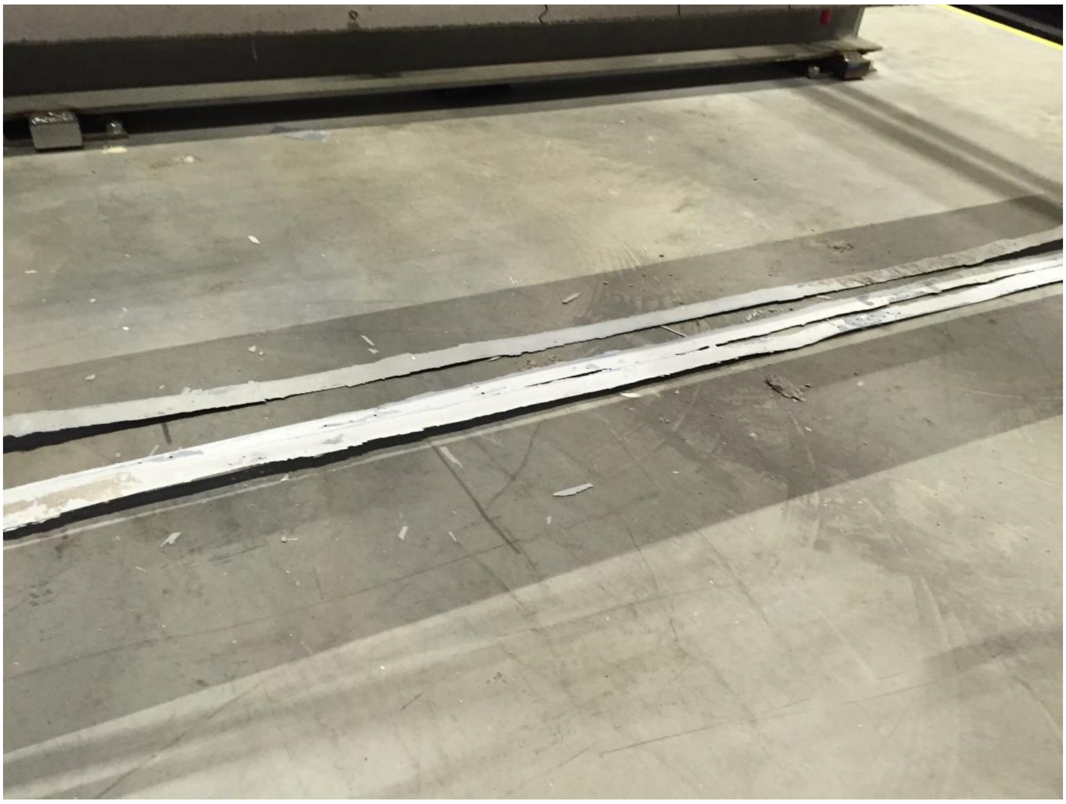


Control sample failure mode

Photos of the Beam test



Reinforced beam 1 failure mode



Reinforced beam 1 failure mode

Photos of the Beam test

Reinforced beam 1 failure mode

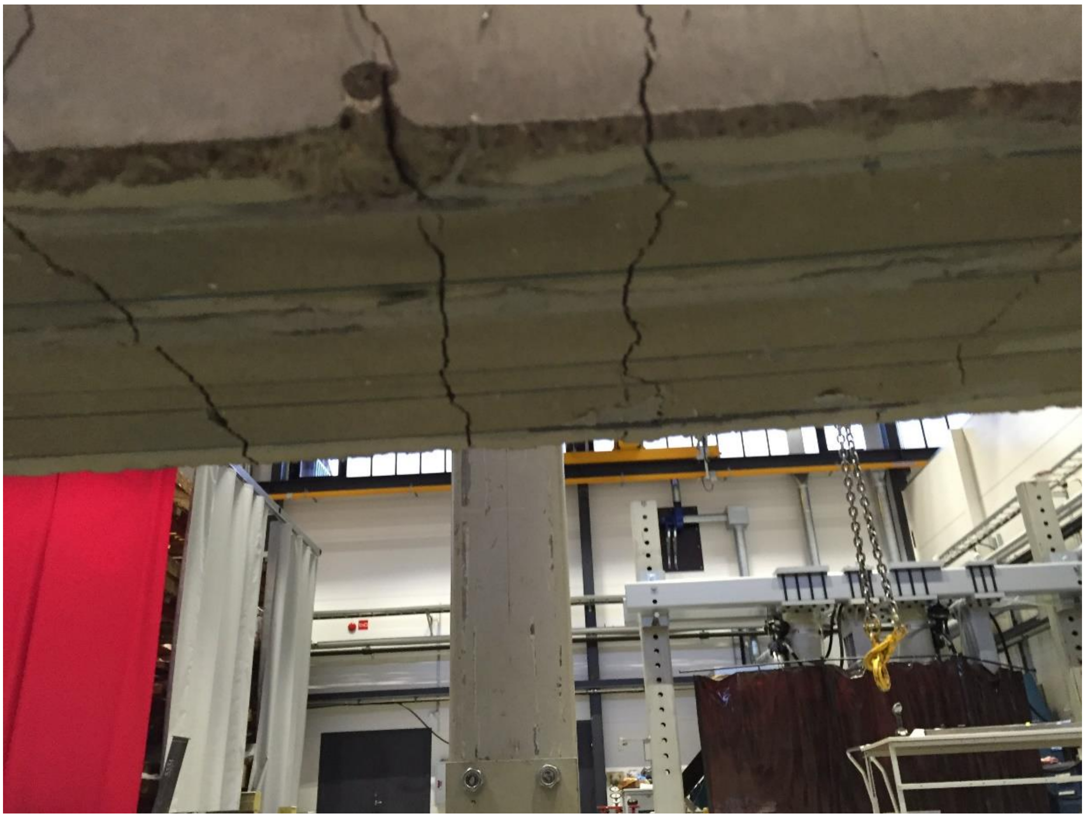
Reinforced beam 2 failure mode

Photos of the Beam test

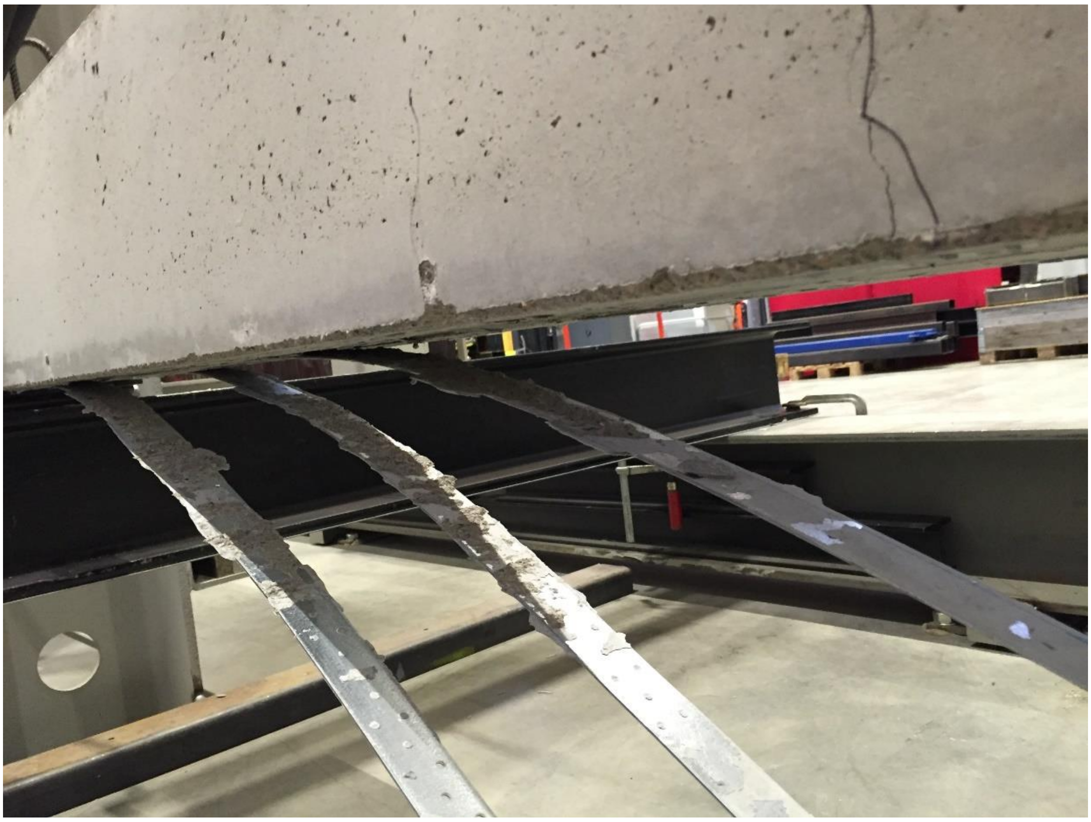

Reinforced beam 2 failure mode


Partially reinforced beam failure mode

Photos of the Beam test



Partially reinforced beam failure mode



Partially reinforced beam failure mode