UNIVERSITY OF TWENTE.

Bachelor's Thesis

Civil Engineering

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Abstract

Shelter, being a fundamental human need, has witnessed technological advancements in construction materials. The present bachelor's assignment explores the integration of fibre-reinforced composite basalt fibre bars as an alternative to traditional steel reinforcements with a view to integrating it into the Dutch construction industry. The research begins by outlining the contextual background, research objective, questions, and approach. The first research question is addressed through two sections: a cross-comparison of steel and fibre-reinforced polymer (FRP) reinforcement codes and an identification of knowledge gaps. The second research question is covered in a single section focusing on practical aspects. The conclusions highlight the results of the analysis of both theoretical and practical knowledge existing in the Russian Federation. The study concludes that FRP reinforcement codes require higher design and long-term load safety factors compared to steel reinforcement design codes. Knowledge gaps are identified, and the Russian experience is assessed to provide insights for Dutch engineers. Note that both Russian codes and field experience have been critically examined, which in some cases led to a conclusion that the studied sources should not be considered reliable in certain aspects. While the Russian market for basalt fibre reinforcement shows potential, some significant challenges such as societal issues and weaknesses in fire resistance and seismic performance are posed. Further research is recommended to address these limitations before widespread adoption in the civil construction industry, particularly in areas exposed to fire.

Contents

1 Introduction

Shelter is one of the most fundamental needs of the human species. Our ancestors learned how to erect, reinforce and repair their living structures prior to developing most of the other fundamental skills such as speech or cultivating plants. Since the early days of construction, we have reached an era where technology is significantly advancing in improving the quality and durability of structures. Structural reinforcements, such as steel rebars, have been an inherent constituent of construction for centuries. However, the trade-offs of steel reinforcements, such as susceptibility to corrosion, relatively high weight and significant environmental impact have urged researchers to explore alternative materials. In the current thesis, one of such alternatives in the form of concrete reinforcement made of fibre-reinforced composite basalt bars is investigated in the context of integration into the Dutch construction industry.

Composite materials can be defined as a "heterogeneous mixture of at least two different materials in micro-scale, possessing new properties other than that of its constituents and usually an almost homogeneous structure in macro-scale." [12] On a micro level, fibre-reinforced composite materials are composed of "two fundamental constituents: fibre and the matrix." [12] The fibres are the form of reinforcement material surrounded by the binding matrix laminate keeping them in place.

Fibre-reinforced composites can be classified into four groups according to their matrices: metal matrix composites, ceramic matrix composites, carbon composites, and polymer matrix composites (PMCs)[12]. The typical polymers are represented by polyester, vinyl or epoxy and will be the only type of matrix considered in this project, being referred to as Fibre Reinforced Polymers (FRP). The visualisation of the structure of the fibre-reinforced composite material can be seen in Figure 1.

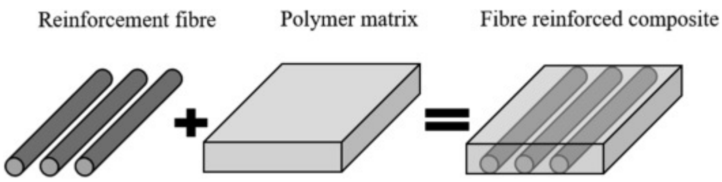

Figure 1: Fibre-reinforced composite [12]

Note that there is confusion in the literature: while some authors refer to FRC as Fibre Reinforced Composite, others imply Fibre Reinforced Concrete with the abbreviation. However, fibre-reinforced concrete is fundamentally different from the studied technology since this type of concrete contains dispersed fibres rather than bars made of fibre composites. [9] In the scope of the current thesis, FRC means Fibre Reinforced Composite. To further specify the type of the matrix in the composite, the term FRP (Fibre Reinforced Polymer) will be more often used. Having established that, the concrete with reinforcement bars made of basalt fibre reinforced composite will be further referred to as "concrete reinforced with BFRP bars", where "B" refers to basalt, which is the main studied material of the current thesis.

Note that the current thesis focuses only on the non-prestressed aspect of the theoretical and practical investigation of the BFRP bars technology. Although Russian codes and practices include extensive information on the prestressed bars, it is decided together with the ABT supervisor Niki Loonen to omit it in the current paper due to the time constraints and complexity of the topic. Hence, throughout the current paper from now on the reader should assume that non-prestressed concrete is implied unless specified differently.

The thesis is structured as follows: first, the research structure in the form of context, objective, questions and approach shaping the research are outlined. Secondly, the first research question is answered with two sections: "Cross comparison" and "Knowledge Gap" with each focusing separately on two sub-questions. However, the second research question is covered in a single section "Practice". Subsequently, the findings from the main 3 chapters are critically analysed and complemented in the discussion section. Finally, the conclusions of the research are made that are complemented with critical recommendations for further research.

2 Research structure

2.1 Problem statement

Application of basalt fibre bars reinforcements in concrete is a new technology that is barely realised in Europe. The novelty of the concept leads to the natural knowledge gaps, that in the given context are primarily reflected in the lack of norms and guidelines [1]. At the same time, the technology has been extensively developed and applied in Russian Federation. Therefore, the current thesis is focused on the investigation of the practices of primarily the Russian Federation and other countries that have more experience with the application of basalt reinforcement to identify possibilities for integration of the technology into the Dutch construction industry.

2.2 Research objective

To conduct an analysis of existing knowledge on basalt reinforcement bars in concrete that can contribute to the integration of the technology in the Dutch construction industry by investigating and comparing internal practices and norms of the Russian Federation to resources already available in English.

By the term integration, it is implied that the conclusions of the project aim at largely contributing to clarifying the possible applications of the technology in the Netherlands. For the format of the analysis, it is aimed to provide a structured and critical overview of knowledge that can be inferred from the Russian codes that may serve as a foundation for the normative basis in the Netherlands. Moreover, the analysis aims at including practical pieces of advice concerning the application of the basalt fibre rebars technology based on the experience of the Russian Federation.

2.3 Research questions

The first research question aims at exploring the existing **normative** knowledge directly relevant to the integration of concrete reinforced with BFRP bars technology in the Dutch construction industry.

1. What knowledge from the current norms in the Russian Federation concerning concrete reinforced with BFRP bars can be borrowed by the Dutch construction industry?

This research question can be approached by breaking it down into sub-questions. Firstly, the main design codes are investigated to identify the difference from the steel alternative. Secondly, sources beyond design norms such as production and testing standards are analysed to select the information that can fill knowledge gaps in the current understanding of BFRP technology. Following this logic, 2 sub-questions are formulated:

1.1 What are the current **design norms** specific to BFRP bars concerning reinforced concrete elements in the Russian Federation?

1.2 What knowledge concerning BFRP bar reinforcement is available in **Russian sources** that fulfils the gaps in the existing English language resources and can be borrowed by the Dutch construction industry?

The second research question aims at exploring the existing **practical** knowledge directly relevant to the integration of concrete reinforced with BFRP bars in the Dutch construction industry.

2. What are the current practical knowledge concerning BFRP rebar-reinforced concrete in Russian Federation that can be borrowed by the Dutch construction industry?

This research question can be approached similarly to the first one by breaking it down into 2 sub-questions related application of BFRP technology. For convenience, differentiation between possibilities and limitations is made that are analysed separately:

2.1 What are the possibilities and benefits of the application of the concrete elements reinforced with BFRP bars based on experience in Russian Federation?

2.2 What are the limitations and challenges of application of the concrete elements reinforced with BFRP bars based on experience in Russian Federation?

2.4 Research framework

As can be seen in Figure 2, the necessary data is going to be collected in four ways: a literature study of the norms and regulations on the basalt fibre reinforcements, a literature study of the application of the technology, expert interviews, and a study of websites of the companies in the industry.

The information available in English on codes and practices accessible for Dutch engineers is mainly retrieved from FIB Bulletin 40 and is used to set a context for the selection of the relevant norms and guidelines of the Russian Federation, which with further processing yields results of the analysis specified in the research objective.

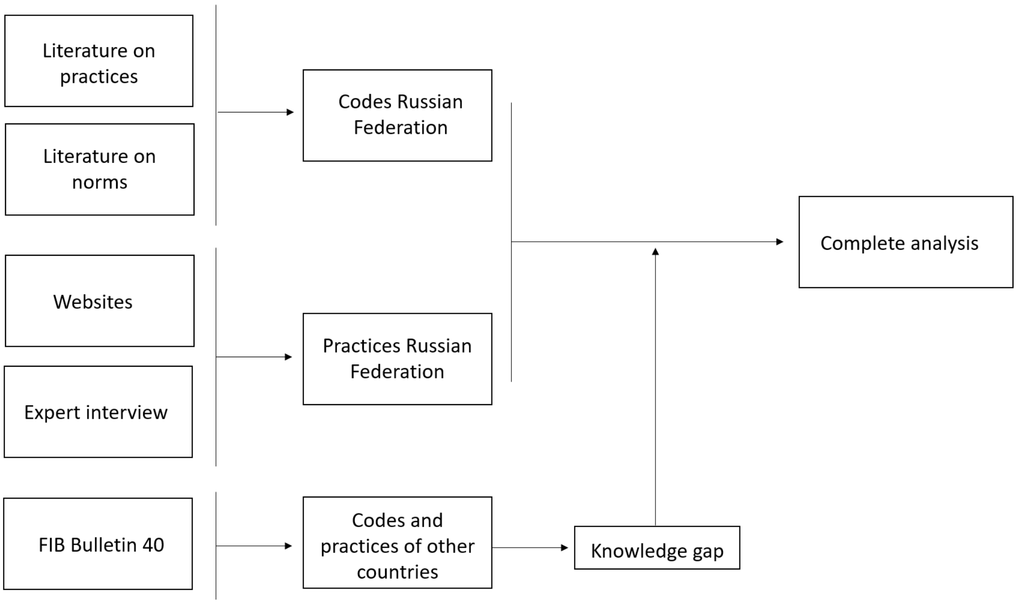

Figure 2: Plan of research

The literature study has been conducted using journal articles found on Google Scholar and Scopus. The codes and regulations not present in the articles were searched with the use of Google and Yandex (Russian) search engines. For the study on practices, the websites of the companies in the field were accessed with Google and Yandex, while the media of these companies were viewed with LinkedIn and Youtube. Finally, the interviews with Russian experts were conducted via Zoom, while other minor input was obtained directly from personal communication with ABT engineers.

2.5 Methodology

The research questions in this thesis are approached in 3 chapters. The first main chapter is called "Cross comparison" (see Section 3). The purpose of this section is to identify the difference in the designing principles between FRP and steel reinforcement by performing a cross-comparison between two Russian codes shown in Table 1. By doing this, research question 1.1 is approached.

Code	Name	Notes
SP 63.13330.2018	Concrete and Reinforced Concrete Structures	Steel
SP 295.1325800.2017	Concrete Structures Reinforced with Polymer Composite Reinforcement	FRP

Table 1: Overview of codes for cross-comparison

Note that there are two types of standards in the Russian Federation: GOST and SNIP (SP). The difference between Russian GOST (State Standard) and SNIP (Construction Norms and Rules) in construction lies in their nature and scope. The main difference between GOST and SNIP is that GOSTs set standards for specific products, materials, and technologies, while SNIPs (codes) define requirements for the designing, construction and operation of buildings and structures.

Both of the investigated codes are structured similarly. Therefore, the cross-comparison is performed chapter by chapter. Although the direct comparison with the Dutch steel reinforcement code [3] falls outside the scope of the current thesis, the outcome of the analysis is structured in a way similar to this code to facilitate further investigation. Namely, the analysis yields 3 sections: Structural ULS (Ultimate Limit State control), SLS

(Serviceability Limit State control), and Design requirements. Note that there are certain limitations of the scope of the investigated codes, which has influence on the applicability of the results obtained further. The exact consequences of the limited scope are investigated in Section 6.1.

The second main chapter is called "Knowledge Gap" (see Section 4). The purpose of this section is to identify the knowledge available in Russian sources that can directly fill in the gaps in the literature available in the English language. By doing this, research question 1.2 is approached.

International Federation for Structural Concrete (FIB) is the International Federation for Structural Concrete is an international organization that focuses on advancing the knowledge and application of concrete and concrete structures. In particular, the FIB Bulletin 40 (2007) "FRP Reinforcement in RC structures" is an exhaustive summary of most of the existing developments in the field accompanied by several newly proposed methods. [6] Bulletin 40 covers the experience of most of the countries that have been developing FRP technology up to the level of a design code or a recommendation.[6] The FIB covers: American Concrete Institute design recommendations (ACI Committee 440 - 2006), Norwegian NS3473, Canadian Standards Association Recommendation (CSA), Canadian Highway Bridge Design Code, Japan Society for Civil Engineering (JSCE recommendation), Italian National Research Council recommendation (CNR), and British IStructE

However, because of unknown reasons, the FIB Bulletin 40 does not cover developments of the technology taking place in the Russian Federation (former USSR) despite the vastness of its scale. Therefore, it is assumed that FIB Bulletin 40 is an acceptable representation of the FRP bars technology development across the globe except for the Russian Federation. To act upon the absence of analysis of Russian standards and codes, first of all, the knowledge gaps outlined in FIB Bulletin 40 are identified. Secondly, the missing knowledge is attempted to be researched within Russian codes. Lastly, the overview of the location and relevancy of the found information is made. For the search of missing knowledge, a few most relevant Russian standards and codes are used:

1. SP 295.1325800.2017 [17]
2. GOST 31938—2022 [22]
3. GOST 31938—2012 [21]

Moreover, the ISO 10406-1:2008 [7] is extensively used for cross-comparison since GOST 31938—2012 is in non-equivalent correspondence with the international standard. [21] This means that the ISO was used as a base for the Russian standard that got complemented by locally available knowledge and experience.

The last main chapter is called "Practice" (see Section 5). The purpose of this section is to identify the practical knowledge available in Russian sources that can contribute to the integration of BFRP reinforcement bars in the Dutch construction industry. By doing this, research questions 2.1 and 2.2 are approached. This section is mainly the executive summary of the data obtained from conducted and prerecorded interviews with experts and websites of companies and manufacturers leading the industry. To provide an objective overview of the findings, both opportunities and weaknesses of the application of the BFRP reinforcement bars are presented in separate subsections.

2.6 Involved parties

For the sake of transparency, the table 2 outlines all the parties that have been involved in a thesis project with their respective roles, interest and participation context.

Stakeholder	**Role**	**Name**	**Interest**	**Participation**
ABT	Client	Niki Loonen	Usable research	Research facilitator , content moderator, assessor
ABT	Client	Jasper van Alphen	Usable research	Research facilitator , content moderator
UT	Supervisor	Gerrit Snellink	Completed project	Content moderator, consultant, assessor
External	Expert	Buchkin Andrey	Voluntary help	Interview input
External	Expert	Osnos Sergei	Voluntary help	Interview input

Table 2: Overview of involved parties

3 Cross comparison

3.1 Ultimate Limit State

3.1.1 Safety factors

Firstly, the design value of the modulus of elasticity for both steel and composite polymer reinforcement (E_s, E_f) should be taken equal to its nominal value.[18] [17] Secondly, for the steel reinforcement, design strength R_s calculation is found using the nominal strength $R_{s,n}$ and safety factor γ_s, where $\gamma_s = 1.15$ for ULS and 1.0 for SLS analysis [18] (see Equation 1).

$$R_s = \frac{R_{s,n}}{\gamma_s} \tag{1}$$

On the other hand, for the FRP reinforcement, the design strength R_f is found using additional factor γ_{f_1} as shown in Equation 2.

$$R_f = \frac{R_{f,n} \cdot \gamma_{f_1}}{\gamma_f} \tag{2}$$

The γ_f for FRP bars is taken as 1.0 similarly to the steel for the SLS analysis, while for the ULS it is determined based on the "coefficient of variation of material properties ν" [17], as shown in Table 3. Dependency of γ_f on the coefficient of variation of material properties ν shows that codes for FRP conservatively take into account the fact that the quality of production of the bars is currently non-homogeneous among manufacturers (see Section 5.4).

ν	γ_f
≤ 0.1	1.2
$[0.1; 0.15]$	1.5

Table 3: Partial safety factor for ULS in FRP

Moreover, the additional factor γ_{f_1} is a coefficient that takes into account the operating conditions of a structure with a composite polymer bar that for basalt is 0.9 for the indoors and 0.8 for the outdoors and in the ground constructions. [17] Note that this coefficient is different for the other types of FRP.

The manual permutations analysis of the possible combinations of γ_f and γ_{f_1} is performed for the current thesis, which shows that the total divisor safety factor analogous to the γ_s (for steel) is ranging in the interval of [1.1(1);1.875]. The mean value of the range (assuming uniform distribution) is 1.4875 and, hence, it can be argued that, on average, the FRP reinforcement codes require by 29.3% higher safety factor for the design strength compared to 1.15 of steel bars.

However, when designing a structure for the action of only permanent and long-term loads, the calculated value of the tensile strength of composite polymer reinforcement should be reduced further as shown in Equation 3 (not to be confused with the factor of general operating conditions γ_{f_1}).

$$R_f = R_{f,n} \cdot 0.4 \tag{3}$$

On the other hand, for the structures reinforced with steel, the comparable long-term strength reduction factor is 0.9. [18] It can be, therefore, seen that, in general, for constant long-term loads, the safety factor for the BFRP bars is significantly higher. However, there is a number of reasons related to the novelty of the FRP technology and properties of basalt fibres that influence this factor and have the potential to change in the nearest future (see Section 5.4).

The design strain for both steel and FRP reinforcement (ε_s,ε_f) is calculated as a fraction of the respective design values of the strength and modulus of elasticity E_s and E_f of steel and FRP respectively as shown in Equation 4.

$$\varepsilon_{s/f} = \frac{R_{s/f}}{E_{s/f}} \tag{4}$$

3.1.2 Bending moments

Russian codes utilise two principally different methods of strength calculation of normal sections of reinforced elements: the limit state test and the non-linear deformation model. Strength calculation of normal sections with composite polymer reinforcement located at the upper and lower faces of the section with the shape of:

- Rectangular beam
- T-beam
- I-beam

as well as compressed structures with rectangular, annular or round cross-sections are allowed to be calculated with the use of the limit state test.[17] Other structures are required to be analysed with the non-linear deformation model, which can be useful when it is necessary to take into account features of materials or complex interactions in a structure. The non-linear deformation model is a less conservative method and allows for a more accurate consideration of the actual behaviour of the structure and can be useful for analysing complex or unusual situations [15]. These principles and conditions hold for both steel and FRP reinforcement.[17] [18]

Russian codes make extensive use of the ratio between the value of the relative height of the compressed zone of concrete (see Equation 5)

$$\varepsilon = \frac{x}{h_0} \tag{5}$$

This ratio is compared with the "boundary relative height of the compressed zone " ε_R defined by Equation 6:

$$\xi_R = \frac{x_R}{h_0} = \frac{\omega}{1 + \frac{\varepsilon_f}{\varepsilon_{b2}}} \tag{6}$$

where

ω — the characteristic of the compressed zone of concrete, determined for heavy concrete of classes up to B60, to be equal to 0.8, for heavy concrete of classes B70 - B100 and for fine-grained concrete - 0.7;

ε_f — is the design value of the limiting relative strains of the composite polymer reinforcement

ε_{b2} — strain of compressed concrete under stresses R_b determined according to SP 63.13330

At this height the limiting state of the structure occurs simultaneously with the achievement in the stretched composite polymer reinforcement stress equal to the design strength (see Figure 3).

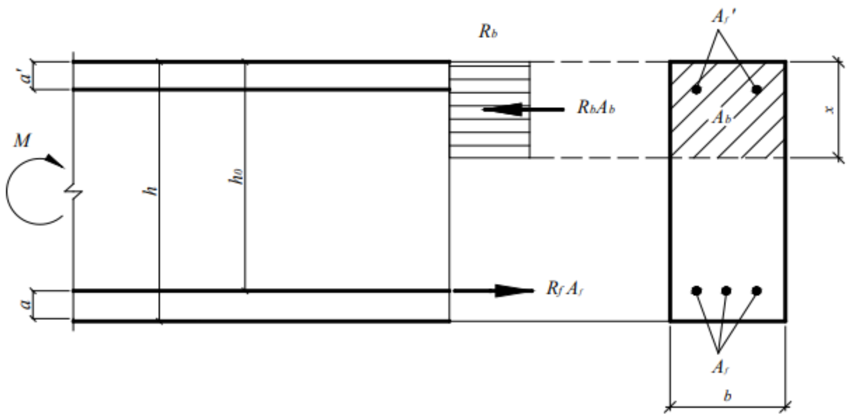

Figure 3: Stress diagram of the bent beam [17]

In general, for structures with the specified above sections subject to bending moments, the condition of $\varepsilon \leq \varepsilon_R$ is required. However, specifically in the FRP code, a separate condition for $\varepsilon > \varepsilon_R$ is specified for strength analysis of bent structures of the T-section or I-section with a flange in the compressed zone. In this case, the analysis should be carried out according to the non-linear deformation model.

The global overarching difference between the FRP and steel reinforcement code stems from the fact that FRP bars show poor behaviour in bearing compression, unlike steel bars. Therefore, although the mechanical principals of ULS calculations are the same, all the formulas for FRP are missing components corresponding to the compression capacity. For example, the limit bending moment, which can be withstood by a rectangular section of the element for the steel reinforcement bar is determined by Equation 7 [18]

$$M_{ult} = R_b \cdot b \cdot x \cdot (h_0 - 0,5x) + R_{sc} \cdot A'_s \cdot (h_0 - a') \tag{7}$$

where height of compression zone x is determined as shown in Equation 8

$$x = \frac{R_s \cdot A_s - R_{sc} \cdot A'_s}{R_b \cdot b} \tag{8}$$

Where (consistent with Figure 3):

R_b — normative resistance of concrete to axial compression

b — width of the cross-section

R_{sc} — design resistance of reinforcement to compression

$A_s^{'}$ — area of the upper reinforcement

While for the FRP, the equivalent limit state bending moment and corresponding x are found by Equations 9 and 10 respectively [17]. As can be seen, indeed, the terms containing R_{sc} are absent since it is equal to 0 for the FRP bars.

$$M_{ult} = R_b \cdot b \cdot x \cdot (h_0 - 0,5x) \tag{9}$$

$$x = \frac{R_f \cdot A_f}{R_b \cdot b} \tag{10}$$

The other large discrepancy between the steel and FRP codes comes in the case when the area of the tensile reinforcement is assumed to be larger than it is required to meet the condition $\varepsilon \leq \varepsilon_R$. In this case, the x in ultimate bending moment M_{ult} calculation for steel is assumed to be as shown in Equation 11. [18]

$$x = \varepsilon \cdot h_0 \tag{11}$$

While for the FRP reinforcement bar, it is determined with a much more elaborate Equation 12 [17].

$$x = \sqrt{(0,5\mu_f \alpha_2 h_0)^2 + \mu_f \alpha_2 h_0^2 \omega} - 0,5\mu_f \alpha_2 h_0 \tag{12}$$

with

$$\mu_f = \frac{A_f}{b \cdot h_0}; \alpha_2 = \frac{E_f}{E_{b2}}; E_{b2} = \frac{R_b}{\varepsilon_{b2}}$$

where

ε_{b2} — limit state value of the relative deformation of concrete in compression

E_f — modulus of elasticity of composite polymer reinforcement

3.1.3 Longitudinal forces

Strength calculation of **eccentrically compressed elements** depends on whether $\varepsilon \leq \varepsilon_R$ or vice versa and is the same for FRP as for the steel except for the terms with a compression capacity of the bars are omitted being equal to 0. However, for the calculation of the critical axial force with Equation 13, factor D (structural rigidity at the ultimate strength stage) has an extra term for the steel reinforcement (see terms with index "s" in Equation 14), which is most likely the consequence of the assumption that FRP does not significantly contribute to the compressive capacity of the element.

$$N_{cr} = \frac{\pi^2 \cdot D}{l_0^2} \tag{13}$$

$$D = k_b E_b I + k_s E_s I_s \tag{14}$$

Calculation of **structures in axial tension** is the same for FRP as for the steel with appropriate values of normative tensile strength. Calculation of **structures in eccentric tension** differs depending on the location of applied longitudinal force and is the same for FRP as for the steel with appropriate values of normative tensile strength and omission of the terms with a compression capacity of the fibre bars.

3.1.4 Non-linear deformation model

As mentioned before, in specific cases, design calculations of the strength and deformation in the section normal to the longitudinal axis structures are performed on the basis of a non-linear deformation model illustrated in Figure 4. The description of the entire model comes outside of the scope of the current thesis and can be looked up in both of the studied codes.

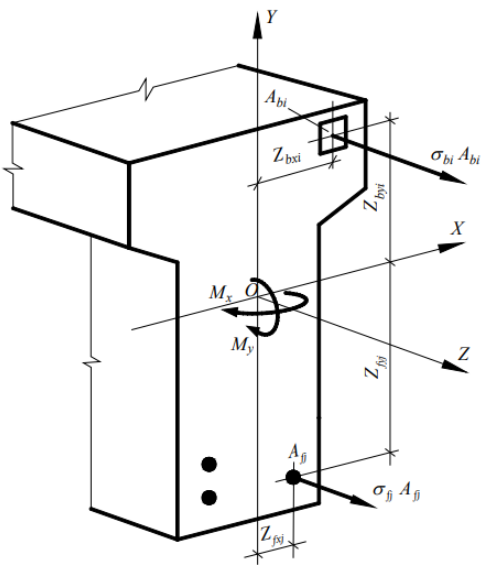

Figure 4: on-linear deformation model diagram [17]

Largely, the equations in the model are the same for FRP as for the steel except for the fact that in the equations establishing the relationship between stress and strain (see Equation 15 [18]), the coefficient (v_{sj}) of elasticity of considered reinforcement bar for FRP , unlike for the steel, is not present i.e. is equal to 1.

$$E_{sj} = \frac{\sigma_{sj}}{v_{sj} \cdot \varepsilon_{sj}} \tag{15}$$

In general, the coefficient of elasticity $v_{s,j}$ is determined by the stress-strain diagram of the bar. For steel, in practice, bi-linear or tri-linear diagrams are used. In the elastic region of these diagrams, $v_{s,j}$ is equal to one, while in the other regions, it is smaller than one since the transformed modulus of elasticity of the bar decreases. At the same time, FRP bars do not show inelastic behaviour and experience abrupt rupture without a significant creep. The above-mentioned concepts are illustrated on the diagram borrowed from SP 63.13330.2018 adjusted to demonstrate the difference in the behaviour of steel and FRP reinforcement bars (see Figure 5). Note that the elastic region of FRP bar is less steep due to its Young's modulus being around 3 times smaller than the one of the steel bar, while the rupture of the FRP bar is not shown since it is attained at over 150% of the ultimate tensile strength of steel. [4].

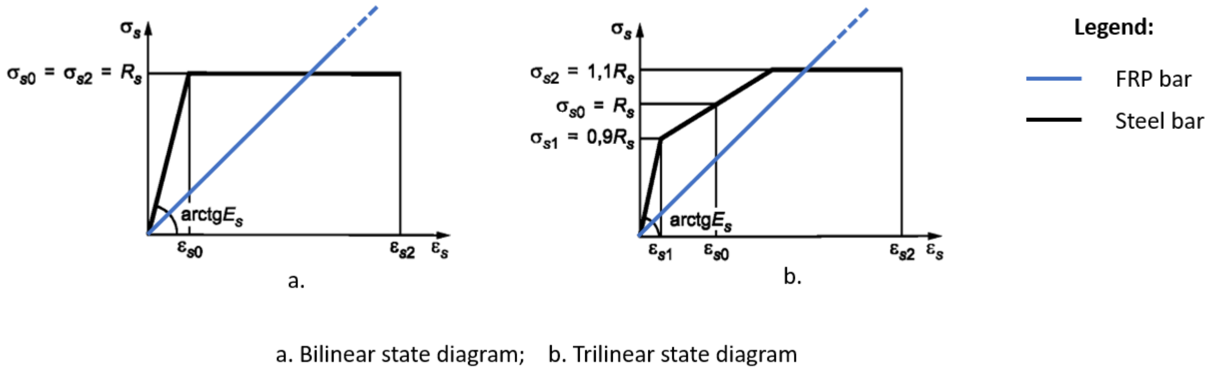

Figure 5: Stress-stress diagrams for steel and FRP bars

Therefore, the fact that the coefficient of elasticity in Russian codes is equal to 1 for FRP is logical since then Equation 15 implies that there is a direct proportionality between stress and strain with the modulus of elasticity being the proportionality coefficient. As shown above, this is, indeed, the case for FRP for its entire stress-strain curve. Therefore, it is concluded that exactly the same non-linear deformation model is used for the calculation of FRP strength with correction for its brittle fracture properties.

3.1.5 Shear forces

Calculation of structures along a strip between inclined sections, along inclined sections for the action of transverse forces and along inclined sections for the action of torsional moments for FBR, are performed the same way as for the steel reinforcements. The same holds for the calculation of structures for local compression and punching.[17] The FRP code does not specify any differences and directly refers to the steel code for these characteristics. Note that resistance of FRP bars to shear forces might be not intuitive for Dutch engineers and is discussed further in Section 6.3.

3.2 Serviceability Limit State

The SLS analysis includes the following points for both steel and FRP reinforcements:[17] [18]

- calculation for the formation of cracks
- calculation for crack opening
- deformation calculation

3.2.1 Moment for cracks formation

The bending moment during cracking should be determined based on the mechanical model taking into account the inelastic deformations of the tensile concrete according to or according to the inelastic deformation model. In general, both methods for FRP are the same as for the steel reinforcement but some equations (e.g. moment of inertia of the reduced section of the element relative to its centre of gravity) omit the terms representing compression properties of the reinforcement bar.

3.2.2 Crack width control

The total crack width is determined in the same way for both the FRP and steel reinforcement according to Equation 16.[17] [18]

$$a_{crc,i} = \varphi_1 \cdot \varphi_2 \cdot \varphi_3 \cdot \psi_f \cdot \frac{\sigma_f}{E_f} \cdot l_f \tag{16}$$

where:

φ_1 — coefficient taking into account the duration of the load: for short term load 1.0, for long-term load 1.4

φ_2 — coefficient taking into account the profile of longitudinal composite polymer reinforcement taken to be 0.7 (for reinforcement of a periodic profile)

φ_3 — coefficient taking into account the nature of the loading: for elements subject to bending and eccentric compression 1.0 , for stretched elements 1.2

ψ_f — stress in longitudinal tension reinforcement in a normal section with a crack from a corresponding external load

l_f — the base distance between adjacent normal cracks

While φ_1 and φ_3 coincide for both steel and FRP reinforcement, the φ_2 coefficient for FRP is fixed to be 0.7 (for reinforcement of a periodic profile). At the same time, the steel reinforcement code differentiates between the bars of a periodic profile (0.5) and smooth reinforcement (0.8). Later it will be shown that the FRP reinforcement cannot be of a smooth profile and therefore such a discrepancy is logical. However, it is not immediately intuitive why the φ_2 coefficient for FRP with the periodic profile is closer to the smooth reinforcement analogy in steel rather than the periodic one. Most likely it has to do with the conservative approach in setting the codes for FRP, which is reasoned in Section 5.4.

Nevertheless, implicitly there is a difference in the base distance between adjacent normal cracks l_f for the steel and FRP reinforcements. The base distance is a quantity that does not take into account the influence of the type of reinforcement surface. For FRP reinforcement it is found with Equation 17, while for steel with Equation 18.

$$l_f = 0,25 \cdot \frac{A_{bt}}{A_f} \cdot d_f \tag{17}$$

$$l_s = 0,5 \cdot \frac{A_{bt}}{A_s} \cdot d_s \tag{18}$$

where:

A_{bt} — cross-sectional area of the concrete in tension

A_f — cross-sectional area of the FRP bar in tension

d_f — nominal diameter of FRP bar

As can be seen, the base spacing between cracks for FRP is assumed to be exactly twice as small compared to the steel reinforcement. Moreover, the boundaries for l_f and l_s quantities for FRP reinforcement are $[10d_f; 20d_f]$, while for the steel one — $[10d_s; 40d_s]$, where $d_f(d_s)$ is the nominal diameter of the FRP and steel reinforcement respectively.

The maximum allowed crack width for steel highly depends on the type of steel used.[18] Also, there is a differentiation between short- and long-term loads.[18] The FRP code does not make a differentiation between fibres for specification of the maximum allowed crack width but still distinguishes the time span of the load.[17] The overview of the respective maximum allowed crack widths is presented in Table 4.

	FRP	**Steel**
Short-term, [mm]	0.7	[0.2; 0.4]
Long-term, [mm]	0.5	[0.1; 0.3]

Table 4: Maximum allowed crack width

As can be seen, the crack width for FRP-reinforced elements is significantly higher compared to the steel alternative, which is caused by the lower elasticity modulus of FRP bars. However, the findings of Russian codes regarding the crack spacing are not intuitive and are not completely consistent with the general crack theory, which is closely analysed further in Section 6.2.

3.2.3 Analysis of deflection

Deflections of structures are determined according to the general rules of structural mechanics, depending on bending, shear and axial deformation characteristics of the element in sections along its length (curvature, shear angles, etc.). The values of the maximum allowable deformations of the elements are taken in accordance with SP 20.13330 [20] and regulatory documents for specific types of structures for both steel and FRP reinforcement. [18] [17] Therefore, it can be concluded that Russian codes don't make a distinction between the type of reinforcement for the specification of the allowable deflection of the elements. However, although the method of calculation is the same, it is expected that the beam with FRP experience larger deflection due to its lower stiffness and thus require more reinforcement.

3.2.4 Mechanical model of deformation

The curvature r of the element in Russian codes is determined in two ways: based on the classical curvature mechanical model and the non-linear model. The mechanical model is based on the flexural behaviour of the beam described with Equation 19 for both FRP and steel reinforcement bars.

$$\frac{1}{r} = \frac{M}{D} \tag{19}$$

where

M — bending moment from the external load

D — flexural rigidity that is for both cases with and without cracks determined as $E \cdot I_{red}$

I_{red} — moment of inertia of the reduced cross-section about its centre of gravity-dependent on the presence or absence of cracks.

Flexural rigidity D of section of concrete elements reinforced with FRP bars is calculated the same way as for steel except for the fact that the moment of inertia of the cross-sectional areas of the compressed reinforcement relative to the centre of gravity is omitted for FRP. Therefore, in the formula for calculating the transformed moment of inertia I_{red} of the element relative to its centre of gravity, the FRP code has by one fewer term. [18] [17] Note that strictly speaking there is differentiation made between the case of cracked and uncracked concrete. For example, for uncracked case the cross-section of the entire concrete is used in the formulas, while for the cracked case — only the area of the compressed part. However, differences between calculation of transformed moment of inertia for the cracked and uncracked concrete are the same in steel and FRP codes and, therefore, are not desctibes in this report.

Furthermore, transformed moment of inertia I_{red} depends on the average height of the compressed zone of concrete that takes into account the influence of the work of tensioned concrete between cracks (x). This quantity in some cases is determined in different ways for FRP and steel reinforcement. For the rectangular section, the steel code specifies both cases: for the reinforcement in pure tension and in tension combined with compression, while the FRP one specifies only the tension case for which both codes use Equation 20.

$$x_m = h_0 \left(\sqrt{(\mu_f \alpha_{f1})^2 + 2\mu_f \cdot \alpha_{f1}} - \mu_f \cdot \alpha_{f1} \right) \tag{20}$$

where

$\mu_f = \frac{A_f}{b \cdot h_0}$, for which the terms are illustrated on Figure 3

However, for the T- and I-shape beams the formulas used to calculate the depth of the compression zone are different. The FRP code uses Equation 21, while the steel reinforcement code utilises Equation 22. It might seem that these equations differ again only by the absence in FRP the compression properties term but a closer examination shows that they are significantly divergent from each other mathematically.

$$x_m = h_0 \left(\sqrt{\left(\mu_f \alpha_{f1} + \mu'_f\right) + 2\left(\mu_f \cdot \alpha_{f1} + \mu'_f \cdot \frac{h'_f}{2h_0}\right)} + \left(\mu_f \cdot \alpha_{f1} + \mu'_f\right) \right) \tag{21}$$

where

$\mu'_f = \frac{A'_f}{bh_0}$; A'_f - cross-section area of the compressed fledge.

$$x_m = h_0 \left[\sqrt{\left(\mu_s \alpha_{s2} + \mu'_s \alpha_{s1} + \mu'_f\right)^2 + 2\left(\mu_s \alpha_{s2} + \mu'_s \alpha_{s1} \frac{a'}{h_0} + \mu'_f \frac{h'_f}{2h_0}\right)} - \left(\mu_s \alpha_{s2} + \mu'_s \alpha_{s1} + \mu'_f\right) \right] \tag{22}$$

Note that all the coefficients α with different indexes are transformation factors dependent on the presence or absence of cracks, the nature of the bar (steel or FRP) and the nature of the load (tension or compression) that are used to calculate the transformed moment of inertia of the section. Although the description and definition of these coefficients is intentionally omitted in the current thesis, they can be looked up in both of the studied codes.

3.2.5 Non-linear model of deformation

Determination of the Curvature of reinforced Concrete elements based on a nonlinear deformation model is performed in the same way for both steel and FRP reinforcement. The only significant discrepancy is in the fact that the coefficient of elasticity of the particular (j-th) rebar (v_{sj}) for FRP is not present in the stress expression unlike for the steel (Equation 23). For the reasoning of this fact see Section 3.1.4).

$$\sigma_{sj} = \frac{E_{sj} \cdot v_{sj} \cdot \varepsilon_{sj}}{\psi_{sj}} \tag{23}$$

Moreover, the coefficient ψ_{sj} in the expression above for FRP is calculated differently. For steel the Equation 24 is used, while FRP code utilises Equation 25.

$$\psi_{sj} = \frac{1}{1 + 0,8\frac{\varepsilon_{sj,crc}}{\varepsilon_{sj}}} \tag{24}$$

$$\psi_{sj} = 1 - \frac{1}{1 + 0,8\frac{\varepsilon_{sj,crc}}{\varepsilon_{sj}}} \tag{25}$$

where

$\varepsilon_{sj,crc}$ — the relative strain of the tensile reinforcement in the section with the crack immediately after the formation of normal cracks;

ε_{sj} — the average relative strain of the tensile reinforcement crossing the cracks at the considered stage of the calculation.

3.3 Design requirements

The Russian code differentiates between two types of reinforcement: principal and structural. Principal reinforcement takes the forces arising under the action of the dead weight and external loads on the structure. Structural (distributive) reinforcement ensures the integrity of the structure as well as the distribution of the action of concentrated forces or impact loads over a large area. The rods of the principal and structural reinforcements are welded (for steel) or tied into a single spatial frame or flat meshes, while structural reinforcement is sometimes used in order to give the reinforcement frame the necessary rigidity. [16]

3.3.1 Cover thickness

For the FRP reinforcement, the thickness of the concrete protective layer of the principal reinforcement should be taken at least 20 mm for prefabricated structures and at least 25 mm for monolithic structures. While for structural reinforcement, the minimum thicknesses of the cover are taken 5 mm less than those required for the principal reinforcement. In all cases, the thickness of the cover should be taken not less than the diameter of the reinforcement bar. [17]

For the steel principal reinforcement, 4 different cases are formulated with the minimum cover ranging in the interval of [20; 40] millimetres:

1. Indoors at normal and low humidity
2. In enclosed spaces with high humidity (in the absence of additional protective measures)
3. Outdoors (in the absence of additional protective measures)
4. In the ground (in the absence of additional protective measures), in foundations in the presence of concrete preparation

For the structural steel reinforcement, the minimum thicknesses of the protective layer of concrete are similarly allowed to be taken 5 mm less than those required for principal reinforcement. In all cases, the thickness of the protective layer of concrete should also be taken not less than the diameter of the reinforcement bar and not less than 10 mm. [18] It can be concluded that the cover required for FRP reinforced structures is smaller or equal compared to those reinforced with steel bars, while FRP code also has fewer cases specified, which is reasoned in Section 6.4

3.3.2 Minimal spacing

The minimum distances between rebars should be such that it ensures the joint operation of reinforcement with concrete and high-quality fabrication of structures, associated with the laying and compaction of the concrete mixture, but not less than the largest diameter of the rod, and also at least:

- 25 mm - for the horizontal or inclined position of the rods during concrete casting, for the lower reinforcement located in one or two rows;
- 30 mm - the same as above for the upper reinforcement;
- 50 mm - the same as above with the location of the lower reinforcement in more than two rows (except for the rods of two lower rows), as well as with the vertical position of the rods during concrete casting

Under cramped conditions, it is allowed to arrange the rods in groups - bundles (without a gap between them). In this case, the distances between the bundles must also be not less than the transformed diameter of the rod, equivalent in terms of the cross-sectional area of the reinforcement bundle calculated with Equation 26.

$$d_{f,red} = \sqrt{\sum_{i}^{n} d_{fi}^2} \tag{26}$$

where

d_{fi} - diameter of one rod in a bundle,

n - number of rods in the bundle.

The principles, limits and formulas described in this section hold for both FRP and steel reinforcement bars. [18] [17]

3.3.3 Principal reinforcement bars

Both FRP and steel reinforcement codes set the boundaries for the value of the minimal sectional area of longitudinal tensile reinforcement $\mu_{f/s}$ similar to Eurocode 2. It is expressed as a percentage of the sectional area of concrete, equal to the product of the width of a rectangular section or the width of a rib of a T-section (I-section) and the working height of the section (see Equation 27)

$$\mu_{f/s} = \frac{A_{f/s}}{b \cdot h_0} \tag{27}$$

Based on the slenderness ratio λ (see Equation 28), the minimum values of $\mu_{f/s}$ are specified differently for FRP and steel reinforcement, which is summarised in Table 5. Note that for the in-between values of λ, the interpolation is supposed to be used.

$$\lambda = \frac{l_0}{i} \tag{28}$$

where

l_0 - design length of the element

i - the smallest radius of inertia of the element

	$\lambda \leq 17$ (for rect. sec. $\lambda \leq 5$)		**$\lambda \geq 87$ (for rect. sec. $\lambda \geq 25$)**	
	FRP	**Steel**	**FRP**	**Steel**
In bent, eccentrically tensioned elements and eccentrically compressed elements	0.13 %	0.1 %	-	-
In eccentrically compressed elements	-	-	0.33%	0.25%

Table 5: Minimum required values of the sectional area of longitudinal tensile reinforcement

However, for the FRP reinforcement, an additional condition is specified that is absent for the steel bars. Namely, the sectional area of longitudinal tensile reinforcement $\mu_{f/s}$ must be additionally greater than the quantity found by Equation 29.

$$\mu_{f/s} \geq 26 \cdot \frac{\overline{R}_{bt}}{R_{fn}} \tag{29}$$

where

$\vec{R}_{bt}$ - average tensile strength of concrete

R_{fn} - normative tensile strength of FRP

Finally, there is a maximum distance between the axes of the longitudinal reinforcement bars specified for structures. Largely, these limits are identical for both FRP and steel reinforcement except for two of them:

1. In beams and slabs for cross-sectional height $h > 150mm$ the maximum for FRP is 300mm, while for steel — 400mm
2. In the walls, the distances between the rods of both vertical and horizontal reinforcement must be less than 300 mm for FRP and less than 400mm for the steel bars

Therefore, it can be concluded that the sectional area of longitudinal tensile reinforcement is required to be on average higher for the FRP reinforcement than for steel, while the maximum distance between the axes of the longitudinal reinforcement bars must be lower for FRP bars.

3.3.4 Transverse reinforcement stirrups

In general, all the information on the transverse (shear) reinforcement in the FRP code is identically present in the steel code as well. However, the code for the steel reinforcement bars contains almost twice as many described cases with corresponding limitations. It can be assumed that the missing cases in the FRP code are not applicable to this type of reinforcement and therefore are omitted. A closer look at the missing cases will be made in Section 5. For now, only the application cases present in the FRP reinforcement code are listed:

1. In continuous and ribbed slabs
2. In beams and ribs with a height of $\geq$ 150 mm, as well as in often-ribbed slabs with a height of $\geq$ 300 mm
3. In eccentrically compressed linear elements in places of inflexions

3.3.5 Anchoring of reinforcement bars

While the steel reinforcement code specifies 5 different ways of anchoring, the FRP code argues that reinforcement anchoring must be implemented in the form of a straight end of the rod (straight anchoring) or using special anchor devices at the end of the rod. Moreover, it is argued that straight anchoring may only be used with ribbed reinforcement.

The base anchoring length is calculated the same way for both steel and FRP reinforcement using Equation 30.

$$l_{0,an} = \frac{R_f \cdot A_f}{R_{\text{bond}} \cdot u_f} \tag{30}$$

where

A_f — the cross-sectional area of the anchored reinforcement bar

u_f — the perimeter of its section, determined by the nominal diameter of the bar

R_{bond} — the design adhesion resistance of reinforcement to concrete, assumed to be uniformly distributed along the anchoring length

The adhesion resistance R_{bond} is determined for steel bars using Equation 31.

$$R_{\text{bond}} = \eta_1 \cdot \eta_2 \cdot R_{bt} \tag{31}$$

where

η_1 — coefficient taking into account the influence of the type of surface of the reinforcement

η_2 — coefficient taking into account the influence of the diameter of the reinforcement

For steel η_1 varies between 1.5 and 2.5, while for FRP it is fixed to be 1.5. This means that Russian codes equate the bonding properties of the periodic FRP bar profile to the smooth steel bar profile (most likely for extra safety reasons, which is consistent with the finding of Section 16). Moreover, the factor η_2 is absent for FRP reinforcement, which is not deemed to have a significant impact in the scope of the current thesis since it is not equal to one only for pre-stressed structures. It can be, therefore, concluded that, in general, with the given load and cross-sectional area, the base anchoring length of FRP reinforcement is larger than the one of steel reinforcement.

The factual anchoring length l_{an} for the steel reinforcement is determined using Equation 32, while the formula for FRP omits the α_1 coefficient.

$$l_{an} = \alpha_1 l_{0,an} \frac{A_{s,cal}}{A_{s,ef}} \tag{32}$$

where

α_1 — coefficient that takes into account the influence of the stress state of concrete and reinforcement on the length of the anchoring and the structural solution of the element in the anchoring zone

$A_{s,cal}$ — cross-sectional areas of the reinforcement required by the calculation

$A_{s,ef}$ — the cross-sectional areas of the reinforcement actually installed

For steel, the factor α_1 is equal to 1 in all the cases except for the beams subject to compression (0.75), which cannot be the case for FRP reinforcement bars since they, in general, do not bear compression. Hence, in all the cases applicable to FRP reinforcement, α_1 is equal to 1 and, therefore, is logically not included in the FRP code.

Although it falls out of the scope of the current thesis, it is worth mentioning that the FRP code does not include the specifications of anchoring pre-stressed structures, unlike the steel code. The reason for it is not immediately intuitive since the FRP code does contain a section on ULS and SLS analysis for the pre-stressed elements.

3.3.6 Connection of reinforcement bars

Similarly to anchoring, the steel reinforcement code contains a variety of types of connection of reinforcement bars, while the FRP code argues that only the overlap type of connection is possible. [18] [17]

For steel reinforcement code, the minimum required connection length is specified with Equation 33 with α_2 being equal to 1.2 for the periodic profile bars with straight ends in tension. For the FRP reinforcement, the α_2 coefficient is specified to be 1.6. Therefore, it can be concluded that Russian codes require a 33% larger connection length of FRP reinforcement compared to the steel alternative.

$$l_{an} = \alpha_2 l_{0,an} \frac{A_{s,cal}}{A_{s,ef}} \tag{33}$$

The minimal distance between adjacent overlap joints and 2 out of 3 absolute minimum boundary conditions for the overlap length is specified to be the same for both FRP and steel reinforcement. However, it is required that the overlap length in any case for FRP reinforcement is $\geq 0.65 \cdot l_{0,an}$, while for the steel reinforcement, this condition is $\geq 0.4 \cdot l_{0,an}$. Therefore, it is concluded that, in general, the required overlap length of FRP reinforcement is greater than the one of steel alternative, according to Russian codes.[18] [17]

4 Knowledge Gap

To visualise the allocation of information pieces from Russian codes matching knowledge gaps from FIB Bulletin 40, the schematic overview is presented in Figure 6. The diagram shows to which Russian code or standard the knowledge pertains. Moreover, it is colour coded according to 3 levels of perceived usefulness, where green implies that the found information fits the gap well and has the potential to be utilised, while red stands for the relatively low novelty of the uncovered piece of knowledge. Every topic is elaborated on in detail further in this chapter.

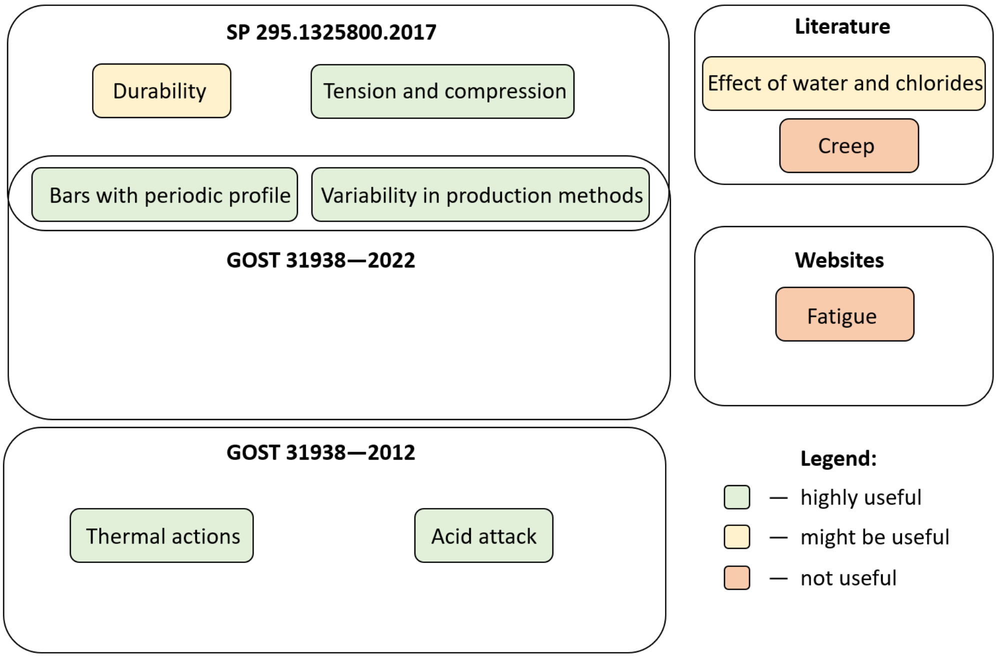

Figure 6: Overview of Russian codes

4.1 Variability in production methods

Nowadays, there is no internationally accepted and unified production method of FRP, which leads to high variability in existing techniques.[6] However, Russian codes partially resolve this issue by setting clear requirements for the properties of the produced FRP bar and formulating the statistical procedure for determining the acceptable deviation and error. GOST 31938—2022 in the chapter "Technical requirements" provides an exhaustive list of parameters that the manufacturers must comply with while producing the FRP reinforcement bar so that it can be used for designing structures according to the Russian design code. [22] The list of required properties is summarised in Table 6. Note that the coefficient responsible for the resistance of FRP bars to compression and shear forces might be not intuitive for Dutch engineers and are discussed further in Section 6.3.

Property	Limit
Tensile strength σ_t, [MPa]	1000
Tensile modulus E_f, [GPa]	50
Ultimate compressive strength σ_c, [MPa]	300
Ultimate shear strength τ_{sh}, [MPa]	150
Tensile strength of adhesion to concrete τ_Γ, [MPa]	12
Reduction of ultimate tensile strength after soaking in alkaline medium $\Delta\sigma_t$, [%]	20
Strength limit of adhesion to concrete after soaking in an alkaline environment τ_Γ, [MPa]	10
Maximum operating temperature T, [°C]	90
Longitudinal porosity	Dye penetration is not allowed for 15 minutes
Water absorption, [%]	0.15

Table 6: Required properties [22]

Moreover, GOST 31938—2022 contains a chapter titled "Requirements for statistical indicators of strength characteristics and Methods for their determination". As can be deduced from its name, the first part of this chapter sets requirements for manufacturers to guarantee average values of limit state values in different batches. In the second part, the chapter describes the procedure that a user can utilise to manually test compliance of the information provided by the supplier with the specified standards. Among others, this procedure includes the selection of a sample, timeline and statistical methods for the analysis of obtained data.

4.2 Effect of water and chlorides

Although non of the studied Russian design codes specifies the influence of water and chlorides on the BFRP, the composite bars, according to these codes, are advised to be used in the aggressive environment in particular. There is external research that shows that the FRP reinforcement undergoes significantly less degradation in its bearing capacity compared to steel (see Figure 7). When exposed to a humid environment, BFRP, on average, stabilises after a loss of 30% of its tensile strength.[26]

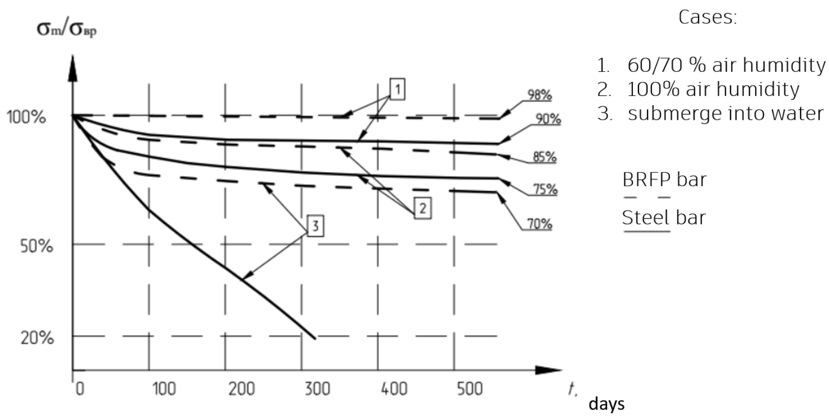

Figure 7: Influence of humidity on properties [26]

It is concluded, that the knowledge of the effect of water and chlorides described in Russian codes is limited and hence has a moderate added value for Dutch engineers.

4.3 Thermal actions

According to FIB 40, the literature study leads to the conclusion that temperatures over 60°C may cause significant issues for FRP, but further research is needed to make robust recommendations. [6] Although GOST 31938—2012 is largely based and is in line with ISO 10406-1:2008, in terms of the thermal effects on the FRP the Russian code in the chapter "Method for determining the operating temperature limit" goes considerably further than the international standard. While the ISO is mainly focusing on determining the thermal expansion coefficient [7], the GOST 31938—2012 describes in detail how the critical operational temperature for BRFP should be found.[21] The method is based on the analysis of the thermo-mechanical diagram obtained when testing a sample for transverse three-point bending to a given deflection value and heating the bent sample in a heating chamber (see Figure 8), recording the change in load as the temperature rises. [21]

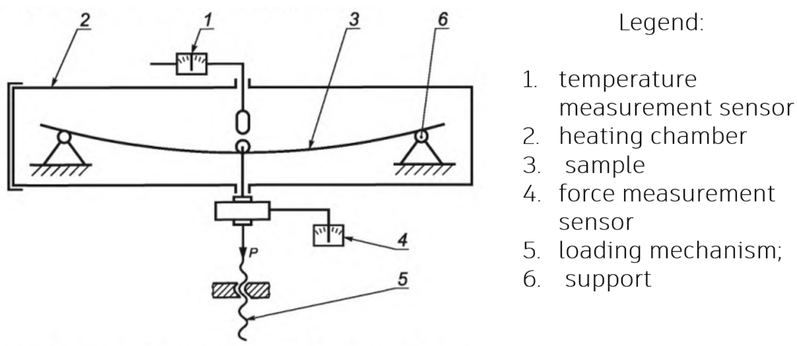

Figure 8: Test set-up for the thermal action experiment [21]

As the temperature rises, the bending resistance of the specimen decreases due to the fact that the resistance of the polymer matrix of the composite to shear stresses reduces. The rate of decrease in the resistance of the sample to bending has a maximum value in the period of time when the heated polymer matrix in the sample begins to soften moving from a solid to an elastic aggregate state. The temperature at which the process of softening the matrix began is determined and considered to be critical.[21]

4.4 Acid attack

According to FIB 40, there is insufficiently little data published on the effects of acid attacks on FRP. It is preliminary concluded that in acid conditions, deterioration of concrete would be of greater concern. However, there is clearly a need to investigate this issue further. [6]

The chapter called "Method for the accelerated determination of resistance to alkalis" of GOST 31938—2012 in large part coincides with the specifications of ISO 10406-1:2008. The greatest overlap is in the conditions and time frame of subjecting the specimen to the alkali environment. [21] [7] However, ISO procedure stops on determining the change of mass of the specimen caused by exposure to the acid, while the Russian standard contains the determination of change in tensile ($\Delta\sigma_t$) and adhesion to concrete ($\Delta\tau_\Gamma$) strength.

The test method coincides with the one described in previous chapters of the code: "Axial Tensile Test Method" and "Determination of Adhesion Strength to Concrete". For calculation of the change in the stress and bonding capacity Equations 34 and 35 are used respectively.

$$\Delta\sigma_t = \frac{\sigma_{t0} - \sigma_{t1}}{\sigma_{t0}} \tag{34}$$

$$\Delta\tau_\Gamma = \frac{\tau_{\Gamma_0} - \tau_{\Gamma_1}}{\tau_{\Gamma_0}} \tag{35}$$

Moreover, as practice shows, the micro-cracks naturally appearing in the FRP bars under load have a significant influence on the alkali resistance behaviour of FRP bars, which is discussed in Section 6.2.

4.5 Durability

The FIB Bulletin 40 argues that there is a need for a unified and exhaustive method to take into account durability in FRP bar design. The main point of critique is that existing guidelines have a single "environmental effect" factor for each FRP material depending on its fibre type. However, there are several environmental effects identified in the literature as contributing: moisture, alkali, temperature and time.[6]

Although the Russian codes do not contain an extensive method that includes all of the mentioned factors separately, there are two safety factors that implicitly account for durability in SP 295.1325800.2017. The first factor γ_{f_1} is in the range [0.8;0.9] and depends on whether the structure is located, indoors, outdoors or in the ground (see Section 3.1.1). Therefore, it can be argued that it indirectly takes into account the alkali and moisture environmental conditions. [17]

Another factor is the coefficient of reduction in tensile strength of composite polymer reinforcement under long-term load. In Equation 3, this factor is shown to be 0.4 for basalt. Since it is required only for the long-term load, it can be concluded that this safety factor takes into account the time constituent of durability. [17]

Nevertheless, the FBI 40 has proposed a significantly more elaborate alternative approach to take into account durability in the design and hence it is concluded, that the durability knowledge described in Russian codes has a moderate added value for Dutch engineers.[6] Although it falls outside of the scope of the current thesis to assess the efficiency of the proposed method compared to the safety factors approach in the Russian codes, it is encouraged to critically investigate this question in further research.

4.6 Tension and compression

According to the FIB 40, the majority of existing research relates to the bending (flexural) behaviour of FRP RC elements, while there is little information on tension and compression. Therefore, there is a clear knowledge gap in this field. [6] SP 295.1325800.2017 contains a few chapters that outline in detail the behaviour of structures in axial tension, eccentric compression and eccentric tension. There is a big overlap in the applied principles with the known steel bar alternative. However, several considerable adjustments are made to account for the peculiarity of FRP properties.[17] The mode detailed explanation on it is provided in Section 3.1.3.

4.7 Bars with periodic profile

The FIB 40 argues that in the case of the deformed steel bars, the interaction arises primarily from the mechanical action of the bar lugs against concrete. On the other hand, for FRP bars bond, interaction has more of a frictional character (see Figure 9). Moreover, the micro-level bond modelling for FRP is not attempted as it is assumed to have a uniform texture.[6] Therefore, it is deduced that Bulletin 40 is missing the perspective of the FRP reinforcement bars with a periodic profile.

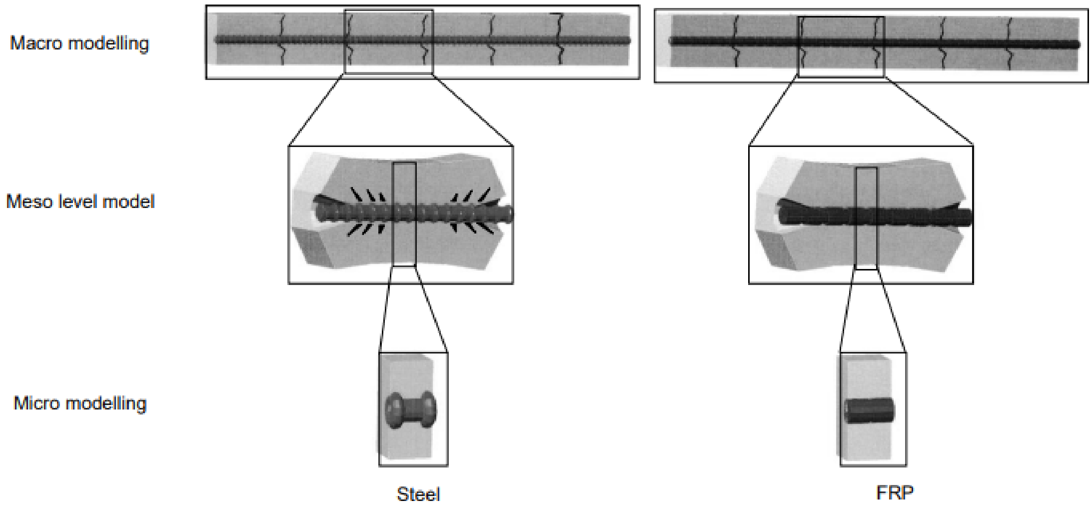

Figure 9: Hierarchy of bond modelling for steel and FRP bars [6]

The main FRP RC Russian code (SP 295.1325800.2017) argues that strictly bars with periodic profiles must be used in designing the FRP-reinforced elements. Hence, the sections "Anchoring of reinforcement bars" and "Connection of reinforcement bars" directly take into account the effect of the lugs on the bonding properties of the bar. The most vivid representation of this can be seen in Equation 31 (Section 3.3.5) and Equation 33 (Section 3.3.6), where both η_1 and α_2 respectively account for the influence of the type of surface of the reinforcement.[17]

Moreover, GOST 31938—2022 specifies the detailed parameters of the periodic profile of the bar that the manufacturer of FRP must comply with.[22] The general scheme of the bar used in the section "Parameters of periodic profile" is shown in Figure 10.

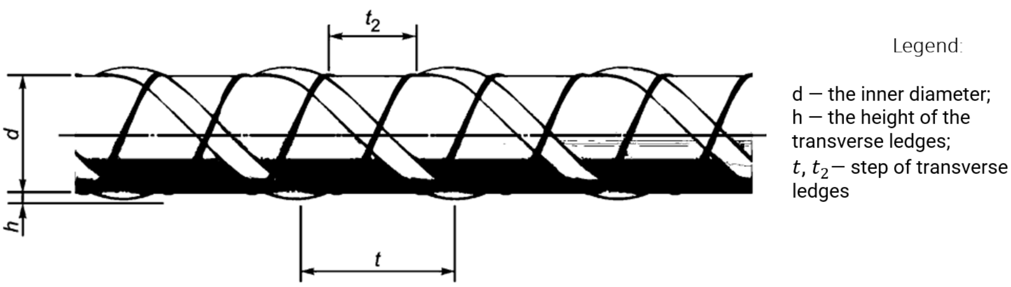

Figure 10: Configuration and parameters of periodic FRP bar profile [22]

4.8 Creep

Creep is a vital concept in designing reinforced concrete elements with a long-term lifespan. Thermosetting resins do not have well-defined melting temperatures, but they tend to degrade when subjected to temperature increases and might cause a significant decrease in the bearing strength capacity of the element. [6] Although there is a number of papers published on this subject, from fundamental to practical aspects, there are few data currently available for endurance times beyond 100 hours [5].

Although Russian FRP codes do not explicitly raise the issue of creep (for non-prestresses elements), research shows that the field of application of composite reinforcement in construction is significantly limited due to its well-known negative properties: creep in time under the action of long-term loads, low modulus of elasticity, low fire resistance. [30] Moreover, the creep is indirectly accounted for by the coefficient of reduction in tensile strength of composite polymer reinforcement under the long-term load described in Section 4.5. Nevertheless, it is concluded that knowledge of creep described in Russian codes has a low added value for Dutch engineers.

Note that creep is taken into account in the design of the pre-stressed elements.[17] Further analysis of this phenomenon falls outside of the scope of the current thesis, however, SP 295.1325800.2017 can be consulted for further research.

4.9 Fatigue limit

Advanced polymeric composites exhibit superior fatigue performance due to their high fatigue limit and resistance to corrosion and there has been significant research done on this topic. [6] Partial safety factors accounting for loss in tensile bearing strength have been developed for aramid, carbon and glass fibre bars, however, the information on basalt is still often missing. [8]

Although Russian FRP codes do not explicitly raise the issue of fatigue, the manufacturers of the BFRP bars conduct tests of their product for fatigue strength. They argue that the fatigue limit based on experiments is $2 \cdot 10^6$ cycles with load variation of 315 to 330 MPa. [29] Hence, it is concluded that knowledge of fatigue described in Russian codes has a low added value for Dutch engineers.

5 Practice

5.1 Analysis of Russian market

In this section, the overall state of the Russian market of FRP reinforcements is outlined to give an impression of the current state of FRP developments in practice. Up to 2018, the share of composite reinforcement, according to market participants, was estimated as 7–10% of the total volume of the building reinforcement market. Currently, there are only two types of products represented on the Russian market of composite reinforcement: fibreglass (65.0%) and basalt-plastic (35.0%). It is argued that the main competitive advantage of fibreglass reinforcement on the market is a significantly lower cost in comparison with basalt-reinforced plastic. [14]

Consumption of composite reinforcement in Russia is limited to two main areas: industrial civil engineering (ICC) ($\simeq$ 85%) and road construction ($\simeq$ 15%). In the field of industrial and civil construction, there are 3 main consumer groups of clients: [14]

1. Concrete concrete plants, reinforced concrete plants and similar enterprises producing prefabricated reinforced concrete (15%)
2. Companies engaged in the construction of industrial and civil facilities (27%)
3. Private developers (59%)

In general, there are in total 130 manufacturers of composite reinforcement bars in Russia including non-certified and small ("garage") industries. However, there are clear market leaders such as "ООО НПК Армастек" that constitutes up to 59.3 % of the production volume. Moreover, the expected annual growth of the basalt composite rebars market in the Russian Federation is 7.5%. Therefore, it can be concluded that the industry of production of basalt composite rebars in the Russian Federation is in the stage of its later development. [14]

5.2 Existing applications

Basalt fibre reinforcement is a rather new technology and, therefore, its application is yet limited in practice. Currently, there are few areas where the basalt fibre reinforcement technology has been applied and has proven to be a reliable technical solution: reinforcement of foundations, industrial floors, and brickwork (meshes, not bars) with basalt [14]

In the existing practice in order to substitute steel bars with basalt composite rebar, the area of reinforcement must be increased by up to 2 times. However, it is argued that in the main scope of application of BFRP bars (in the aggressive environment), all the reinforcement elements must be replaced with FRP at once without leaving any steel parts. This comes through the fact that due to the lower rigidity of composite bars, the cracks in the structure will be wider. In its turn, wider cracks result in exposure to the aggressive environment that is acceptable for basalt bars but becomes detrimental for steel elements in the same structure. (A.Buchkin, personal communication, June 6, 2023) Note that it has been a great challenge to retrieve data on realised projects with the use of BFRP bar reinforced concrete in Russian Federation, which is elaborated in Section 6.5

5.3 Foreseen opportunities

The material has excellent resistance to corrosion and withstands large tensile stress, making it the most attractive material for the aggressive environment of exploitation, where a large life span is required. Examples of aggressive impact are freezing and thawing infrastructure objects, exposure to exhaust and aggressive gases, location in the ground or exposure to water. (A.Buchkin, personal communication, June 6, 2023) These properties make the BFRP reinforcement an outstanding alternative for the construction of:[14] [17]

1. Underground civil structures
2. Mine constructions
3. Sewerage systems
4. Agricultural storages
5. Chemical production sites
6. Toxic waste disposal sites
7. Water treatment and purification facilities
8. Land reclamation
9. Marine and harbour structures

Some specialists argue that BFRP bars can be safely used in civil and industrial low-rise structures in building envelopes or walling. [25] Moreover, basalt, in particular, is transparent to a magnetic field and acts as a dielectric. Therefore, it is beneficial to reinforce structures operating under high electromagnetic fields and potential differences with basalt composite bars. Connected to these properties, the most viable application of the technology would be in supports of power transmission lines, construction of power-plants and other structures, where penetration of electromagnetic field must be prevented [14] [17]

Although not extensively developed yet, the road construction segment should be also considered very promising in terms of the potential application of composite reinforcement. In the context of road construction, the replacement of metal reinforcement with composite allows for the elimination of rutting, preventing damage to the coating, and the formation of various cracks. Therefore, BFRP bars (and meshes) are deemed to be perspective in the following directions:[14]

1. Reinforcement of asphalt concrete pavement
2. Production of concrete slabs for coatings of inter-construction, temporary bypass automobile
3. Strengthening of slopes of embankments and banks of reservoirs
4. Construction of foundations and slopes of roads
5. Construction of retaining walls
6. Strengthening of the roadbed

Furthermore, there is a number of opportunities that relate to the development of the manufacturing of BFRP bars. Firstly, if the fibres are well taut and the standard of manufacturing is met, it is possible to produce bars with a modulus of elasticity E reaching up to 120 GPa instead of 70 GPa. (S.Osnos, personal communication, June 1, 2023) Supporting this argument, the research shows that there are more ways to increase the modulus of elasticity of FRP bars [24]:

1. By changing the composition and structure of the composite material, by using new fillers (e.g. combined fibres), hardeners and a polymer bases
2. By use of shell molds to create higher strength characteristics on the surface of the reinforcement
3. By creating a pre-stressed state in the reinforcement, for example, by torsion

Secondly, BRFP bars are light weigh compared to steel in principle the length of their production is limited only by the transportation means. It is argued, that bars of at least 200 meters can be manufactured. (S.Osnos, personal communication, June 1, 2023)

Thirdly, in the case of application of the structure in a non-aggressive environment, it is possible to combine both steel and BFRP elements since in this case, wider cracks do not result in a detrimental effect for steel bars. (A.Buchkin, personal communication, June 6, 2023) Moreover, the researchers have proven that the increase in the specific surface of the reinforcement directly results in the reduction of the crack width. It is argued that the most efficient way to increase crack resistance with the given reinforcement area is attained by reduction of the diameter of the reinforcement while decreasing the spacing between the bars (more rods of smaller diameter).[28] Hence, it can be concluded that crack width in the concrete elements reinforced with FRP has the potential to be reduced.

Lastly, the sustainability aspect of utilising BFRP bars is undeniable. Research shows that the replacement of only lower steel reinforcement with FRP bar leads to an immediate decrease of environmental impact measured in Global Warming Potential by 8%. Consequently, replacing all longitudinal and shear reinforcements would yield much higher environmental savings [11]. Moreover, the BFRP bars are lighter, not prone to corrosion and require a higher reinforcement area to compensate for the lower modulus of elasticity. Therefore, less cement is required to be used in the design, which immediately reduces environmental impact further.(N.Loonen, personal communication, May 5, 2023) Furthermore, the FRP bars are more durable and hence the life span of the structures reinforced with them increases, which directly makes use of such elements more sustainable. Finally, it is argued that the body frames of industrial products manufactured from basalt fibres such as electric cars can be shredded and reused as volumetric (dispersed fibre reinforcement) of concrete structures and hence reduce the lifecycle CO_2 emissions of the reinforcement. (S.Osnos, personal communication, June 1, 2023) Note, that dispersed fibre reinforcement falls outside of the scope of the current thesis and is mentioned here purely for the integrity of the narration.

5.4 Existing and foreseen challenges

At the same time, there are limiting factors that are actively preventing the market of BFRP bars to develop:

- Conservatism of industrial-civil and road construction industries in relation to the application of innovative technologies
- Underdevelopment of regulatory framework in the road construction segment that defines the requirements for properties, methods, tests and calculation procedures of composite reinforcement;
- Lack of programs and ready-made models for calculating structures using composite reinforcement

There is a number of societal factors tied to the above-mentioned issues that hamper the integration of the BFRP reinforcement technology in Russia. Firstly, there is little motivation for engineers to remake standard designs to embrace the alternative of basalt composite reinforcements. This is reinforced by the fact that for steel bars multiple pre-made design solutions exist that can be easily adjusted for the new projects. Moreover, even for the considered BFRP alternative, it is often not chosen over steel since it can be seen as having no immediate financial benefit for two reasons. The cost is often calculated for the running meter, while the benefit over steel becomes apparent only if the cost per ton is considered. On top of that, the life-long design cost should be calculated instead of the cost of pure construction. Lastly, there is an issue with the system of distribution of finances in general. For example, the road builders are sponsored for repairs rather than building new roads, which leads to no incentive for the contractors to make roads durable. Therefore, governmental reform is needed to stimulate the executive organs to use BFRP reinforcement bars. [28]

Moreover, there are a few main properties that hamper the application of BFRP bars in practice. Firstly, although the basalt fibres can perform well up to 982 $°C$, the epoxy and other types of matrices significantly deteriorate in their bearing properties in the temperature range of [70 to 175 $°C$]. [6] Therefore, the BFRP bar reinforcement elements cannot be used in structures that can be potentially exposed to fire. (S.Osnos, personal communication, June 1, 2023) Secondly, due to the low rigidity of the BFRP bars, it's not always possible to completely substitute steel reinforcements due to the large deformations caused by composite bars. Therefore, in the locations of the greatest bending moments causing tension (e.g. in the foundation slabs), the steel reinforcement is still used even if the rest of the construction is reinforced with FRP mesh. (A.Buchkin, personal communication, June 6, 2023)

Furthermore, the current production of BFRP bars in practice is often far from perfect and deviates from the advised norms. Therefore, the existing standards for durability limit the guaranteed lifespan of the BFRP bar to 50 years which has been shown in multiple experiments. However, it is argued that if the technology of manufacturing was unified and products complied with the properties specified in GOST 31938—2022 [22], the lifespan of the bar could reach at least 100 years. (A.Buchkin, personal communication, June 6, 2023) In other words, the existing standards take into account the statistical uncertainty in the properties of the produced bars, which leads to conservative requirements. Another possible mitigation of the conservatism of the standards is expected to occur in the safety factor for the long-term loads described in Section 3.1.1. Experts say that it is planned to lift the factor up from 0.4 to 0.6 as multiples (or reduce from 2.5 to 1.66 as divisors), which implies that BFRP reinforced structure will experience 1.5 times as little deterioration in bearing capacity with time in comparison to the value assumed in the current design codes. [28]

Finally, although technically speaking it is possible to build high-rise structures reinforced with basalt polymer fibres, in practice, it is not beneficial for multiple reasons. First of all, due to the lower rigidity, the number of stirrups and longitudinal reinforcement area need to be at least twice as large for FRP bars than for the steel alternative to comply with limits for deformations. Secondly, the BFRP stirrups themselves are very expensive since they need to be produced in the exact shape during the manufacturing process since the bar cannot be bent on-site. Thirdly, the BFRP reinforcement would not satisfy the fire safety standards for civil structures due to the mentioned above reasons. Lastly, due to the absence of the possibility of welding BFRP reinforcement, they have to be mechanically tied together, which does not provide sufficient rigidity of the seismic reinforcement belt and therefore cannot be used in plenty of civil structures (A.Buchkin, personal communication, June 6, 2023)

6 Discussion

6.1 Limitation of the studied Russian codes

The Russian construction codes (SP) have specifically defined the limitations of their application. It is important to identify the scope of the codes prior to making a conclusion from the analysis since it might directly affect its validity. In the following section, the relevant conditions are outlined for both steel and FRP reinforcement

Both FRP and steel codes have in common 2 conditions. Firstly, the codes are designed only for the climatic regime of the Russian Federation: systematic exposure to temperatures not higher than 50 C and not lower than minus 70 C. Secondly, both codes assume the use of structures made from heavy, fine-grained, light, cellular and tension concrete.[18] [17]

It is highlighted that the FRP code can only be used for structures operated under static load [17], while the steel code specifies a separate condition to ensure an environment with a non-aggressive degree of exposure. Moreover, there is a number of cases when the steel code is specified to be **not applicable**:

- Hydraulic structures, bridges, road surfaces, airfields
- Structures made of concrete with an average density of less than 500 and more than 2500 $\frac{kg}{m^3}$
- Concretes based on lime, slag and mixed binders (except for their use in cellular concrete), on gypsum and special binders, concretes on special and organic aggregates
- Large-pore concrete structures.

Note that although the FRP code does not explicitly specify the types of structures when it is not applicable, this becomes apparent from the comparison with the steel reinforcement code. Further comments on the structural cases present in the steel and absent in the FRP code are elaborated in detail in the cross-comparison of the two codes. [17] [18]

As can has been shown above, there is a number of structures such as hydraulic structures, bridges etc that are not covered by the studied steel reinforcement code and can potentially be beneficial to reinforce with the basalt bars. Nevertheless, all of these structures have separate codes that determine design principles for taking into account specific structural peculiarities. For example, for bridges, a plastic hinge is allowed in the design, while for other structures it is not (M.Verbaten, personal communication, May 15, 2023).

Therefore, the performed cross-analysis is acknowledged to be initially biased but is it assumed that the comparison of the design of the regular concrete elements with steel against FRP can give a solid base for the initial understanding of other more specific structures as well.

6.2 Crack analysis

The findings of Russian codes are not completely consistent with the general crack theory. Firstly, the crack spacing of FRP reinforcement should be larger than steel since the spacing is a function of the bonding length. As shown in Section 3.3.5, the anchoring length required to develop a full bonding for FRP bars is higher than for steel bars and hence the crack spacing for FRP bars must be also greater. (M.Verbaten, personal communication, June 27, 2023) Secondly, crack width is a function of the deformation of the reinforcement and concrete between adjacent cracks and, therefore, a function of spacing [6], which is consistent with Eurocode 2 (see Equation 36 [3]).

$$w_k = s_{r,\max} \cdot \varepsilon_{cr} \tag{36}$$

where

$s_{r,\max}$ — maximum crack spacing

ε_{cr} — Crack inducing strain in concrete

Therefore, the smaller spacing predicted by SP295.1325800.2017 should cause smaller crack width, which is not the case in Russian codes and hence causes a contradiction. Moreover, some researchers have shown that due to the fact that the base length $f_{s/f}$ is predicted by SP 295.1325800.2017 to be twice as small for FRP-reinforced elements compared to steel, the theoretical data on the width and spacing of the crack opening for all tested beams are underestimated relative to the experimental data by up to 79.4%.[10] Therefore, it can be concluded that the current Russian standard should not be considered a reliable source for methods of crack analysis.

On the micro-scale, there are also cracks appearing in the FRP reinforcement itself that play a significant role in the alkali resistance behaviour of the FRP bar. As practice shows, under load, the emerging micro-cracks in the reinforcement bar lead to the direct exposure of the fibres to the alkali environment. Therefore, in general, and especially in the aggressive environment, both deterioration of fibres and the matrix itself lead to a decrease in the bearing capacity of the reinforcement bar. (S.Osnos, personal communication, June 1, 2023) Note, however, that according to Table 6, the decrease in bearing capacity is not allowed to exceed 20%. Moreover, from the design perspective, the effect of alkali attack is supposedly included in the γ_{f_1} and 0.4 safety factors (see Sections 3.1.1 and 4.5) accounting for the long-term loads, although it is not explicitly mentioned in the codes.

6.3 Differences in paradigms

Firstly, although in Russian steel reinforcement codes taking into account compression strength is a strict guideline, in Dutch practice it is omitted in most of the cases except for columns due to the insignificance of its contribution (N.Loonen, personal communication, May 5, 2023). Therefore, although the absence of compressibility effect is a large difference between steel and FRP Russian codes, it is not of large significance for Dutch engineers.

Secondly, in the Dutch construction industry it is believed that FRP bars cannot bear any shear stress due to its fibre nature, this is not the case, according to the findings in Russian codes (for more information, see Section 4.1). Moreover, this concept also comes in agreement with American research which argues that "the matrix, such as a cured resin-like epoxy, polyester, vinylester, acts as a binder and holds the fibres in the intended position, giving the composite material its structural integrity by providing shear transfer capability" [2]. Nevertheless, although the calculation method for FRP bars is the same as for steel, the shear capacity of FRP bars is 2-3 times smaller than of steel [2] and, therefore, can have a significant influence on the design e.g. require more stirrups in the structure. Lastly, the scale of the values of the required compressing and shear strength specified in Table 6 might be not immediately intuitive due to the idea that fibres cannot withstand compression. Indeed, in the BFRP bar, the compression is entirely taken by the polymer matrix, while for the shear stress, the fibres also take a role. Although the compressive and shear strengths are specified for the purpose of unified quality manufacturing, the findings of the previous section are, nevertheless, relevant and in the design the compression properties of BFRP bars are neglected. (A.Buchkin, personal communication, June 6, 2023)

6.4 Protective cover

The finding of the Russian code that the protective cover is required to be smaller for FRP bars compared with steel corresponds to the purpose of the cover and the nature of the FRP. Namely, the cover is used for 3 reasons: protection of reinforcement against an aggressive environment, ensuring the needed fire resistance and securing the joint work with concrete. However, in the case of composite reinforcement, the cover is determined mainly based on the conditions of joint operation of reinforcement with concrete and fire resistance and, therefore, has less conservative requirements in the codes. (A.Buchkin, personal communication, June 6, 2023) Moreover, there are no environmental cases specified for the FRP reinforcement cover design most likely because it is not susceptible to damage from an aggressive environment, unlike steel. There are also significantly more structural cases specified in the steel code that are missing in the FRP one. For example, meshes and the reinforcement located at the inner faces of hollow elements of an annular or box section are omitted in FRP code. Presumably, this is the case because of the implied non-applicability of the FRP reinforcement bars in the mentioned elements.

6.5 Availability of information

It has turned out to be extremely hard to retrieve the concrete cases of BFRP rebars being implemented in the Russian Federation. One of the main research institutes that has been approached in the course of the current study showed very defensive behaviour not willing to share knowledge with European partners in the context of the current geopolitical situation. The only proposed option to get access to the local materials was for me to go to Russia for half a year and conduct research on the base of this research institute. Unfortunately, this falls outside of the possibilities of the current graduation assignment.

Most of the implemented designs are not publicly announced since they are made without official permission at the risk of the contractor for the sake of e.g. financial benefits of BFRP bars. For example, the vaulted passages and driveways in Sochi have been reinforced fully with basalt bars for the Olympics games 2014 as there was not enough steel immediately available due to logistic difficulties. However, this information has never been published since there is no officially issued permit for this decision. [27] One of the very few announced examples is a bridge in Ulyanovsk that has been built with the use of carbon composite. [13] Namely, the above-ground parts of supports of arched elements and profiled decking were fully reinforced with carbon composite bars (not basalt) [23]

7 Conclusions

In the current thesis, the analysis of existing knowledge on basalt rebar concrete reinforcement technology that can contribute to its integration into the Dutch construction industry has been conducted. The accent has been made on the experience of the Russian Federation, however, other countries have been also considered limited to the sources available in English.

Firstly, the cross-comparison of two Russian codes for reinforcement of concrete with steel (SP 63.13330.2018 [18]) and FRP (SP 295.1325800.2017 [17]) has been made within elaborated limitations. It has been found that FRP reinforcement codes require by 29.3% higher safety factor for the design strength (see Section 3.1.1) and by 127% higher long-term load factor in comparison to steel: 0.4 against 0.91 as multipliers or 2.5 against 1.1 as divisibles. Overall, both codes apply the same structural models for both reinforcement types. However, all the equations are corrected for the absence of an ability to withstand compression and take into account the elastic rupture behaviour of FRP bars. Moreover, for elements reinforced with FRP bars larger cracks are allowed by the codes. However, it is concluded that Russian codes should not be considered a reliable source for methods of crack analysis. Concerning detailing of the elements, the FRP reinforced elements require smaller or equal cover compared to steel, while the required sectional area of reinforcement and anchoring length must be higher with smaller maximum allowed spacing between the bars. Note that the codes argue that for FRP reinforcement, only bars with periodic profiles and straight-end anchoring are allowed to be used.

Secondly, the analysis of the experience of other countries mainly summarised in FIB Bulletin 40 [6], has been conducted. As a result, the knowledge gap consisting of 9 topics was formulated. On each of these topics, an investigation of Russian sources was performed, which resulted in the outline of available complementary knowledge and estimation of their relative utility for Dutch engineers. Namely, tension and compression in FRP bars, bars with periodic profiles, variability of production methods, thermal actions and acid attacks showed to be areas, where Russian resources can significantly enrich knowledge and opportunities of the Dutch construction industry.

Lastly, the practical study of the current situation and field knowledge concerning the application of BFRP bars in the Russian Federation has been conducted. It has been found that there is a relatively large market of BFRP rebars that is in the stage of its active development, having consistent growth potential. The main current application of the technology in Russia finds its place in the form of foundations and floor slabs, with the main potential of further use being in aggressive environments in numerous fields. However, a lot of societal problems hampering the integration of BFRP bars in the construction industry have been found. Moreover, BFRP bars demonstrate apparent weaknesses in terms of fire resistance and seismic performance. Nevertheless, there are clear opportunities for further technological developments in the production of BRFP bars, that can yield higher E and durability properties. This is expected to result in softening of the conservative safety factors. For example, the long-term load factor can be reduced from +127% (2.5) to +52% (1.66) as a surplus compared to steel (1.1) expressed as multiples (see Section 5.4). Therefore, there is a need for further research in the unification of production and in the direction of fire-resistant matrices and seismic rigidity. Until the breakthrough in these aspects, it is strongly advised to abstain from the use of BFRP-reinforced elements in the civil construction industry and limit it to application in aggressive environments not exposed to fire.

8 Recommendations

Although it falls outside of the scope of the current thesis, it has been argued by multiple experts that excessively large deformation of elements reinforced with BFRP bars can be prevented by pre-stressing them. Moreover, Russian engineers have developed anchoring devices for the pre-stressed FRP bars, which significantly enlarges the scope of their application. [27]. Furthermore, for prefabricated structures with FRP reinforcement, the impact of forces arising during their lifting, transportation and installation should be taken with additional dynamic factors, which is not covered in this thesis. [17]

On top of that, Russian norms have been rapidly changing over the past decade. For example, although GOST 31938—2012 was used for inferring knowledge, most of its content was changed in the updated version GOST 31938—2022. Namely, all the tests were moved to the GOST 32492-2015. [19]. Moreover, at the moment of finalising the current paper, the Russian leading research institutions are actively working on revising SP 295.1325800.2017 [17] design code. Therefore, it is strongly advised to study the updated version of this design code in the coming years to trace the occurred developments.

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