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Dissertation abstract
**Modelling and researching the behaviour of strengthened
building structures**

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The dissertation consists of 141 pages, 65 figures, 14 tables

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I. Analysis of the problems of existing structures

Short description of the chapter

In this chapter are discussed:

- 1. Topicality of the problem*
- 2. Analysis of the existing building stock in Bulgaria*
- 3. Defects and damages in existing structures*
- 4. Reliability of building structures*

Some conclusions are made.

1. Topicality of the problem

Currently, towns and villages are built with a very diverse building stock - both new and older buildings of different materials. The density of construction is increasing, especially in the central parts of large cities. The lack of vacant land for new buildings necessitates the adaptation of existing ones to a new function.

The problem of restoring and strengthening existing structures is very relevant. The need for proper interventions on Europe's aging building stock will become increasingly apparent.

2. Analysis of the existing building stock in Bulgaria

The existing building stock of Bulgaria consists of buildings and facilities with various constructions: masonry, reinforced concrete (prefabricated or monolithic), steel, wooden (braided) and mixed (braided construction with brick filling, combined steel-reinforced concrete construction, steel-wooden elements etc.).

The dissertation describes the percentage share of each structure for the number of dwellings and the number of buildings.

Conclusion: As an analysis of the data it can be done that in Bulgaria there is a significant number of masonry structures (with wooden or reinforced concrete floor structures), followed by reinforced concrete, and other types of structures are less common. Focusing on the problems of these buildings is essential for the future development of Bulgarian towns and villages.

3. Defects and damages in existing structures

In order for a strengthened structure to be properly modeled, the strengthening structure must be properly modeled. First, it is necessary for the analysis of the existing structure and secondly it is an important step in the modeling of the reinforced structure.

The dissertation lists the most important defects and damages and we will make the necessary comments related to the real behaviour of the structure and its modeling. Examples will be shown, some of which are from the author's practice as a designer.

3.1. Defects and damages in reinforced concrete structures

3.2. Defects and damages in masonry structures, as well as in masonry, which work as part of the load-bearing structure for horizontal actions of buildings with reinforced concrete skeleton

3.3. Defects and damages in steel structures

3.4. Defects and damages in wooden structures

Conclusion: The modeling of structures with defects and damages is a complex problem that does not always have an accurate and practically achievable solution. Proper (as far as possible) modeling is very important for the right design decision for such structures.

4Reliability of building structures

The concept of "reliability" of building structures is briefly discussed and some examples of amortization of structures are presented.

As a conclusion, for example for brick buildings with wooden floor constructions, it can be said that the replacement of wooden floor constructions with new ones is a good option, as the intervention on the load-bearing brick elements may be less due to their lower amortization over time. .

II. Analysis of the historical development of the regulation in the design of building structures and the existing regulations in the field of restoration and strengthening

Short description of the chapter

In this chapter are discussed:

- 1. Historical development of the regulations in Bulgaria related to actions on buildings and structures other than seismic action*
- 2. Historical development of the regulations in Bulgaria related to antiseismic design of structures*
- 3. Regulations relating to the retrofitting or strengthening of buildings*

Some conclusions are made about the development of the actions on the buildings along the time the constructions are calculated, some conclusions and recommendations are done in the estimation of existing buildings.

1. Historical development of the regulations in Bulgaria related to actions on buildings and structures other than seismic action

The brief review of the history of design standards is useful for the proper assessment of buildings and facilities.

Since the creation of design standards, design statements have changed significantly, and most loads have increased. The first regulations in Bulgaria were Rules for construction of private buildings in the cities of the Bulgarian principality [Правила за строеж на частни здания в градовете на българското княжество] and were established in 1881. With the advent of reinforced concrete as a more widely used material the Regulations for the design of reinforced concrete structures in the Kingdom of Bulgaria were invented. [Правилник за проектиране на стоманобетонните строежи в Царство България].

It should be borne in mind that the older standards work with the admissible stress method with a common safety factor, usually is in the admissible stress of the material. This leads to a certain unpredictability regarding their conservatism compared to the current regulations.

The effects related to the weight of structural elements are determined on the basis of densities, ie. they should not change according to the regulations. Live and climatic actions (snow, wind) are regulated.

The first regulations in Bulgaria are rather informative - wall thicknesses are described and so on. Subsequently, the norms began to impose more calculations, specific physical models of describing the phenomena were imposed.

Моделиране и изследване поведението на усилен строителни конструкции

	Year	Live load residential places		Life loads offices		Live load corridors		Snow	
		Value	Safety coefficient	Value	Safety coefficient	Value	Safety coefficient	Value	Safety coefficient
Правилникъ за натоварванията на сгради и за допустимите натоварвания на почвата при сгради	08.05. 1935г.	2	1*	2	1*	as in the rooms		0,75	1*
Правилник за натоварвания на сгради и за допустимите натоварвания на почвата при сгради	11.01. 1950г.	1,5	1*	1,5	1*	as in the rooms		0,75	1*
Правилник за основните методи при изчисляване на строителните конструкции и за натоварванията на сгради	03.10. 1959г.	1,5	1,4	2	1,4	3	1,4	0,5 or 0,7	1,4
Натоварване на сгради и съоръжения - правилник за проектиране	01.07. 1964г.	1,5	1,4	3	1,4	3	1,3	0,5 or 0,7 or 1	1,4

Натоварвания и въздействия. норми за проектиране	01.09. 1979г.	1,5	1,4	3	1,3	3	1,3	0,4 до 1	1,4 до 1,6
Основни положения за проектирането на конструкциите на строежите и за въздействията върху тях - Наредба №3	16.04. 2005г.	1,5	1,3	3	1,3	3	1,3	0,6 до 2,4	1,4
Система Еврокодове	2007	2	1,5	3	1,5	3	1,5	0,6 до 5	1,5

* The regulations are using the method of admissible stresses and the safety factor is not in the action.

Table 4. Actions according to previous and current regulations

Conclusion: In conclusion, it can be said that all buildings, designed according to regulations after 1935, if they are designed, built and maintained properly, are designed to have sufficient and even commensurate with the current regulations reliability for vertical actions, with some exceptions for climatic effects.

Practice will prove the reduction of load-bearing capacity of structures over the years.

2. Historical development of the regulations in Bulgaria related to antiseismic design of structures

The definitions of seismic actions according to the following regulations are briefly described

2.1. Technical and hygienic standards for earthquake sites

2.2. Regulations for design and construction of buildings and engineering facilities in the earthquake regions of Bulgaria 1947

2.3. Regulations for design and construction of buildings and engineering facilities in the earthquake regions of the People's Republic of Bulgaria, 1957

2.4. Regulations for antiseismic construction, 1961

2.5. Regulations for construction in earthquake areas, 1964

2.6. Standards for the design of buildings and facilities in earthquake areas, 1987

2.7. Ordinance on the design of buildings and facilities in earthquake areas, 2007

2.8 Ordinance on the design of buildings and facilities in earthquake areas, 2012

2.9. BDS EN 1998

An interesting conclusion made in [Ignatiev, N., .P. Sotirov, History of the Bulgarian norms for seismic survey of structures and transition to a structural system Eurocodes, presentation, <http://www.petkovstudio.com/documents/7.pdf>] and [Providing buildings for seismic impacts, KIIP, Engineering Forum, no. 6, 2012] shows that buildings built between 1964 and 1987 should be considered seismically secured, as in most cases the seismic forces in the 1964 Regulations are greater than the seismic forces in the 1987 Regulations. In § 1. item 4 of the additional provisions of Regulation № RD-02-20-2 of 27 January 2012 on the design of buildings and facilities in earthquake areas] it is written that “Unsecured buildings” are the buildings that are built before 1987. "

3. Regulations relating to the retrofitting or strengthening of buildings

3.1. Historical development of regulations related to the inspection, evaluation or reinforcement of buildings

Evaluation, restoration and strengthening of buildings are problems that have always been outside or have been slightly affected by the regulatory framework.

In 42 point of the 1987 Earthquake Design of Buildings and Facilities states that “Unsecured and seismically protected buildings may be rebuilt and upgraded [...] if it is proved that after redevelopment and upgrading the same are seismically secured in accordance with the requirements of these norms ”. This requires that in any reconstruction the building or facility be insured against an earthquake, according to this regulations.

Simultaneously with this document was widely used [Project Association Association Guide 1988]. This guide gives some mitigating requirements and although it is not a normative document it has been used frequently in the past [Traikova, M., Restoration and strengthening of buildings. Problems, constructive solutions, practical examples ISBN 978-954-9897-40-1].

3.2. Bulgarian regulations

In the current regulations in Bulgaria, the problem of evaluation, restoration and strengthening of buildings is addressed in only a few articles. [Regulation RD 02-20-19] and [Ordinance № RD-02-20-2 of 27 January 2012 on the design of buildings and facilities in earthquake areas] provide the main points in the assessment of buildings and facilities and the need for reinforcement. The main idea is that the structures are checked for compliance with the regulations under which they are designed, and if they meet, a positive assessment is given. In case of change, it is not necessary to meet the requirements of the current regulations if the masses do not increase by more than 5%, if there are non-design drilling of openings, which

reduce the bearing capacity and ductility up to 5% and there are defects and damages, displacements of reinforcement and others, which reduce the bearing capacity up to 5%. If the mass increases by more than 5% or there are more serious interventions in the structure, it must be strengthened in accordance with current regulations. Exceptions are immovable cultural values, for which deviations are allowed, although it is not said which ones. The dimensioning of the structure, in case it needs to comply with the current regulations is done according to national standards or Eurocodes depending on the assignment of the contracting authority (for sites 3-6 category, according to the The low for the regulation of the territory) or mandatory Eurocodes for sites 1-2 category or some public procurement. Reconstruction requires technical inspection, compliance with the requirements for maximum allowable height and number of storeys, seismic assessment and investment project.

Some authors [Georgiev, A., V. Penchev, Seismic resistance of buildings designed before March 1, 1987, Stroitel newspaper, 2012] believe that the statement should give a positive assessment of buildings that do not comply with current regulations. system is incorrect. There is logic in this, but in the author's opinion it is not possible to strengthen the buildings, according to the current regulations, because this would require global intervention in any case, and local would lose all meaning. This would unduly burden the country's economy.

In the author's opinion, a positive assessment should be given to buildings designed and implemented according to the norms in force at the time of their design, but also to meet some minimum requirements for seismic safety, for example to be designed for reduced seismicity compared to at the time of assessment current seismic norms. This is a kind of environment that will not require every single structure to be reinforced, but it will not allow buildings and facilities that are totally unsecured from seismic impacts to receive a positive assessment.

3.3. БДС EN 1998-3

Eurocode 8 [БДС EN 1998-3] is specifically dedicated to the seismic assessment of existing buildings. Unfortunately, again, recommendations for non-seismic security are completely missing.

The following features are considered in the dissertation and some comments are made:

3.3.1. Necessary information

3.3.2. Limit states

3.3.3. Methods for analysis of structures

The methods for analysis of the constructions are presented and notes for their practical application are made

3.3.3.1. Linear methods

3.3.3.1.1. Horizontal forces method

3.3.3.1.2. Linear spectral analysis

3.3.3.2. Nonlinear methods

3.3.3.2.1. Method with behaviour factor q

3.3.3.2.2. Static nonlinear pushover analysis

3.3.3.2.3. Method with direct integration of accelerograms (time-history analysis)

3.3.4. Inspection of structures

3.4. American regulations

A number of norms of various organizations in the United States address the problems of strengthening existing structures. These are ATC - 40 (1996), FEMA - 273/274 (1997), FEMA-310, FEMA - 356/357 (2000), KANEPE - (2004), FEMA - 440 (2005), ASCE 41-06), FEMA 547. These are “handbooks”, ie. manuals, the Federal Emergency Management Agency (FEMA) or other organizations.

In the dissertation some productions are briefly considered:

3.4.1. FEMA 310

3.4.2 FEMA 356

3.4.3. FEMA 440

III. Basic theories related to modeling and load-bearing capacity of FRP-reinforced walls. Problems .

Short description of the chapter

In this chapter are discussed:

- 1. Introduction to the problem*
- 2. Load-bearing capacity of a wall, strengthened with vertical and horizontal strips of FRP - prerequisites in different standards*
- 3. Working diagram of the masonry under pressure. Overview of theories*
- 4. Review of scientific developments and experiments in Bulgarian and world practice*

The theoretical and regulation basis on which the sizing of strengthening of walls strengthened with FRP materials lies is described..

1. Introduction to the problem

The dissertation discusses the application, advantages and disadvantages of FRP materials for reinforcement of building structures..

2. Load-bearing capacity of a wall, strengthened with vertical and horizontal strips of FRP - prerequisites in different standards

The dissertation describes the three world standards in this field in terms of their practical application. The admissible stresses and strains in the FRP strips are emphasized. The following are considered:

2.1. ACI440.7R-10

2.2. CNR DT 200/2004

2.3. CNR DT 2000/2004/R1

3. Working diagram of the masonry under pressure. Overview of theories

The dissertation examines the main stipulations in the work of masonry in compression. This is necessary in order to create an interaction M-N diagram.

The following sources are considered:

3.1. Standards for the design of masonry structures

3.2. Eurocode 6

3.3. American standards ACI 530

3.4. CNR DT 200/2004

3.5. Research by various scientists

Conclusion: The accepted admissible deformations and approximations of the working diagram of the masonry in CNR-DT200 / 2004 and ACI 440.7R-10 are appropriate and well confirmed by experiments.

4. Review of scientific developments and experiments in Bulgarian and world practice .

4.1. Experiments in Bulgaria

Relatively few scientific studies on such topics have been conducted in Bulgaria. Most relate to the reinforcement of columns and a few to walls. The dissertation briefly describes the following developments:

4.1.1. Joint experiment of UACEG and ISOMAT

4.1.2. Dissertation of Borislava Nikolova-Kamenarova

4.1.3. Dissertation of Eng. Teodor Todorov

4.1.4. Dissertation of Nikolay Bogdanov

4.1.5. Works by Nikoleta Barakova.

4.2. Experiments around the world

The following experiments are briefly described in the dissertation

4.1.1. Experiment in Colombia [Vega, C., Torres, N. (2018). External strengthening of unreinforced masonry walls with polymers reinforced with carbon fiber. Engineering and Investment, 38 (3), 15-23. DOI: 10.15446 / ing.investig.v38n3.73151 - http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0120-56092018000300015]

4.1.2. Japanese experiment [Rahman, Ataur & Ueda, Tamon. (2016). In-Plane Shear Performance of Masonry Walls after Strengthening by Two Different FRPs. Journal of Composites for Construction. 20. 04016019. 10.1061 / (ASCE) CC.1943-5614.0000661.]

IV. Admissible stresses and strains in FRP strips

Short description of the chapter

In this chapter are discussed:

1. *Admissible stresses and strains in the FRP strips. Theoretical statement*
2. *Admissible force in FRP strip according to the regulations*
3. *Experimental results and their comparison with the theoretical*
4. *Conclusions*
5. *Anchoring length*

Conclusions are in relation to which standard is closest to the experimental results in the world and their conservatism.

1. Admissible stresses and strains in the FRP strips. Theoretical statement

The material from which the strengthening strips are made is very strong, and the most likely form of destruction is debonding of the FRP strips.

Debonding usually occurs by breaking by cutting the base (brick wall, concrete) on which the FRP strip is glued, not in the adhesive layer, because it is stronger, nor on the border of the adhesive layer with FRP strip or base, because the adhesion is big enough. Shear stresses are distributed according to a strongly curvilinear law along the length of the FRP strip and after a certain distance, representing the anchoring length, are very small.

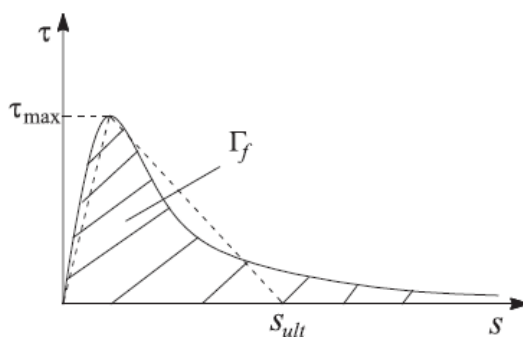


Fig. 56. Diagram of the distribution of tangential stresses with a glued strip of FRP [Francesca Ceroni, Barbara Ferracuti, Marisa Pecce, Marco Savoia, Assessment of a bond strength model for FRP reinforcement externally bonded over masonry blocks, Composites Part B: Engineering, Volume 61, 2014, Pages 147-161, ISSN 1359-8368, <https://doi.org/10.1016/j.compositesb.2014.01.028>.]

The maximum force that the FRP strip can withstand is::

$$F_{max} = b_f \int_0^{\infty} \tau(x) dx$$

The specific energy of destruction Γ_f (in dimension energy / unit area) [Iman Mansouri, Ozgur Kisi, Prediction of debonding strength for masonry elements retrofitted with FRP composites using neuro fuzzy and neural network approaches, Composites Part B: Engineering, Volume 70, 2015, Pages 247-255, ISSN 1359-8368, <https://doi.org/10.1016/j.compositesb.2014.11.023>.] is:

$$\Gamma_f = \int_0^{\infty} \tau(s) ds$$

where s is the slip of the FRP strip relative to the base.

After processing these expressions, assuming the bilinear approximation of the shear stress diagram to s_{ult} , the formulas in the CNR-DT 200 standard for determining the allowable stresses and strains in the FRP bands given in Chapter 3 are made.

2. Admissible force in FRP strip according to the regulations

2.1. Admissible force in the FRP strip according to CNR-DT 200

From the substitution of formulas given in Chapter 3, and taking into account the fact that the calculated maximum force in the amplifier band is $F_{cnr-dt, d} = f_{idd} \cdot b_f \cdot t_f$, we obtain the following formula:

$$F_{cnr-dt, d} = \frac{1}{\gamma_{fd} \cdot \sqrt{\gamma_M}} \cdot b_f \cdot \sqrt{2 \cdot E_f \cdot t_f \cdot f_{mk} \cdot \sqrt{0,1} \cdot 0,015} \quad (5)$$

This force, according to the requirements of the standard for maximum deformations in FRP material, must not exceed:

$$F_{cnr-dt, d, max} = \eta_a \cdot \frac{\varepsilon_{fk}}{\gamma_f} \cdot E_f \cdot t_f \cdot b_f \quad (6)$$

where ε_{fk} – limit strain in FRP, given by the manufacturer.

η_a - conversion factor – it can be taken from table 3.4 of CNR DT 200/2004] and for outer strips of FRP is 0.65 for glass fibers, 0.75 for aramid fibers, 0.85 for carbon fibers

γ_f - safety factor, taken according to table 3.2 of CNR DT 200/2004] and has a value of 1.1 for certified systems and application type A), according to point 2.5 of CNR DT 200/2004] and 1.25 for non-certified systems (type B application)

Hence the characteristic value, without taking into account the safety factors, is obtained:

$$F_{cnr-dt,k} = b_f \cdot \sqrt{2 \cdot E_f \cdot t_f \cdot f_{mk} \cdot \sqrt{0,1} \cdot 0,015} \leq \eta_a \cdot \varepsilon_{fk} \cdot E_f \cdot t_f \cdot b_f \quad (7)$$

According to this formula, the forces that can be compared with the experimental ones can be calculated.

2.2. Admissible force in the FRP strip according to CNR-DR 200 / R1

From the substitution of formulas given in Chapter 3, and taking into account the fact that the calculated maximum force in the amplifier band is $F_{cnr-dt-R1,d} = f_{dd} \cdot b_f \cdot t_f$, we obtain the following formula:

$$F_{cnr-dt-R1,d} = \frac{1}{\gamma_{fd} \cdot \sqrt{FC}} \cdot b_f \cdot \sqrt{2 \cdot E_f \cdot t_f \cdot f_{mb} \cdot \sqrt{0,1} \cdot k_c \cdot \sqrt{\frac{3 - b_f/b}{3 - b_f/b}}}$$

This force, according to the requirements of the standard for maximum deformations in FRP material, must not be greater than that given by the formula

The characteristic value, without taking into account the safety factors, is obtained:

$$F_{cnr-dt,k} = b_f \cdot \sqrt{2 \cdot E_f \cdot t_f \cdot f_{mb} \cdot \sqrt{0,1} \cdot k_c \cdot \sqrt{\frac{3 - b_f/b}{3 - b_f/b}}} \leq \eta_a \cdot \varepsilon_{fk} \cdot E_f \cdot t_f \cdot b_f$$

The designations are given in Chapter 3.

Comment and comparison between CNR-DT 200 and CNR-DT 200 / R1

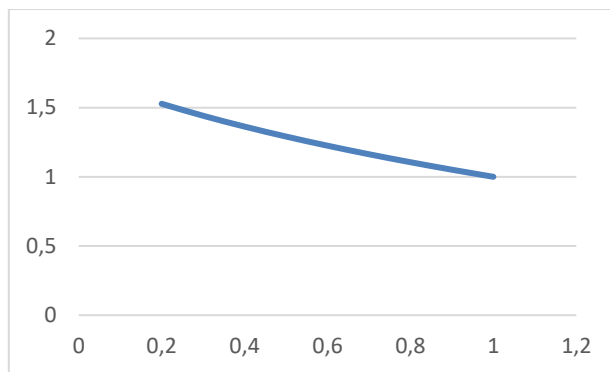
The admissible forces received under the CNR-DT 200 / R1 edition are significantly higher than those received under the original version of the standard, due to several significant differences:

First, the version of the standard uses the average, and in the original version the characteristic value (5% fractil) of the compressive strength of the wall. Given that the strength of a wall is a random variable with a large scatter of the average value (unlike that of steel, for example), this will lead to serious differences.

Second, the coefficient c_1 when determining the specific energy of destruction is replaced by k_c . This coefficient for a brick wall is 0.031, which is more than twice the value of $c_1 = 0.015$.

Third, a coefficient k_b has been added. Let us examine the values of this coefficient from the case when the width of the FRP band is equal to the width of the strengthened element (such a case is almost impossible in practice) to values about 1/5 of the ratio of the effective width of

the FRP band to the width of the strengthened element (5cm strip on a brick wall 25cm, for example).



Фиг. 47. Values of k_b

It can be seen that it is greater than 1, and for the common cases in practice there are values 1,2-1,4.

2.3. Determination of allowable force in FRP bands using the ACI 440.7R-10 methodology

This standard uses a much simpler methodology based on empirical dependencies. Permissible deformations of the reinforcing strip are given with different formulas depending on whether bending or shear damping is being investigated. Since bending fracture results in a clearer and purer stress state, much like that realized in the experiments to determine the force of detachment, this method will be used here to calculate the allowable force in the reinforcing strip.

$$\varepsilon_{fe} = k_m \cdot \varepsilon_{fu} \leq C_E \cdot \varepsilon_{fu} \quad (13)$$

where $k_m = 0,45$ external applied FRP and has other values for other type of application of FRP

C_E – coefficient, which takes into account the type of FRP

ε_{fu}^* - limit strains in FRP

If the failure is due to shear, there is a different and more complicated methodology for calculating the allowable stresses. The difference is in replacement of the coefficient k_m with k_v , as k_v has values from 0.2 to 0.4 depending on the physico-mechanical coefficient of reinforcement with FRP.

The permissible characteristic force in the FRP band, taking into account that $F_{aci, k} = \varepsilon_{fe} \cdot E_f \cdot b_f \cdot t_f$, is:

$$F_{aci,k} = k_m \cdot \varepsilon_{fu} \cdot E_f \cdot b_f \cdot t_f \leq C_E \cdot \varepsilon_{fu} \cdot E_f \cdot b_f \cdot t_f$$

According to this formula, a force can be calculated that can be compared with the experimental one.

3. Experimental results and their comparison with the theoretical

The dissertation presents experimental results from various literature sources around the world. Calculations were made and experimental and theoretical results were compared.

In the absence of data calculations, a deformation deformation of 1.7% was assumed, which is typical for most carbon FRP bands.

Test results in which the destruction is not debonding but another type, such as brick destruction, are not included as not indicative of the allowable strength in the FRP strip. In experiments where the experiment is two-sided, the shear forces for one strip are given, i. half of those experimentally measured.

For greater clarity, a calculated and characteristic value of the force of failure according to CNR-DT 200 is given.

N	E _f , MPa	t _f , mm	f _m , Mpa	b _f , mm	b, mm	ε _{max} , %	Experiment, N min-max		Notes	Pub- lished
1	230000	0,165	17,4	40	120	1,7	10030	10960	l _c =150-200mm, 3x6 exper.	[6]
2	230000	0,165	17,4	60	120	1,7	12480	13670	l _c =160-220mm, 4x3 exper.	[6]
3	230000	0,165	17,4	80	120	1,7	14630	19000	l _c =160-240mm, 5x3 exper.	[6]
4	240000	0,17	7,3	50	120	1,45	13000		l _c =250mm, 1 experiment	[7]
5	200000	0,097	7,3	50	120	1,45	11500		l _c =250mm, 1 experiment	[7]
6	230000	0,165	42,3	50	120	1,5	18100		l _c =200mm, 1x5 experiments	[8]
7	215000	0,117	8,8	25	130	1,7	4340		l _c =150mm, 1x3 experiments	[9]
8	132200	0,172	16,4	50	120	1,87	4540		l _c =200mm, 1x2 experiments	[10]
9	132200	0,172	18,3	50	120	1,87	5780		l _c =200mm, 1x2 experiments	[10]
10	132200	0,172	31,8	50	110	1,87	7360		l _c =200mm, 1x2 experiments	[10]
11	132200	0,172	30,2	50	130	1,87	6850		l _c =200mm, 1x2 experiments	[10]
13	233000	0,17	19,8	50	120	1,26	5870	9070	l _c =160mm, 5x5 experiments	[11]
14	240000	0,165	19,2	50	120		6810		l _c =200mm, 1x3 experiments	[1] *
15	240000	0,17	9,9	50	120		6280	8970	l _c =200mm, 2x5 experiments	[12]
16	240000	0,17	24,9	50	140		17050	18040	l _c =250mm, 4x1 experiments	[13]
17	240000	0,17	40,9	50	140		14800	20400	l _c =250mm, 4x1 experiments	[13]

18	230000	0,17	33,5	50	250	1,6	15940	20150	lc=200mm, 1x5 experiments	[14]
*University of Sannio, internal report										

Table 9. Experimental data for carbon tripes, externally applied on masonry

Ef, MPa	tf, mm	fm, Mpa	bf,	b,	F _{cnr-dt} , N	F _{cnr-dt,d} , N	F _{cnr-dt-R1} , N	F _{cnr-dt-1,d} , N	F _{aci-M} , N	Experiment, N min-max	
230000	0,165	17,4	40	120	3165,93	1865,54	5412,45	3189,32	10400	10030	10960
230000	0,165	17,4	60	120	4748,89	2798,31	7756,93	4570,81	15600	12480	13670
230000	0,165	17,4	80	120	6331,86	3731,08	9901,44	5834,48	20800	14630	19000
240000	0,17	7,3	50	120	2657,80	1566,12	4440,03	2616,31	13000	13000	
200000	0,097	7,3	50	120	1832,71	1079,93	3061,66	1804,10	6329,25	11500	
230000	0,165	42,3	50	120	6170,31	3635,89	10307,90	6073,99	12808,1	18100	
215000	0,117	8,8	25	130	1145,66	675,08	2040,23	1202,22	4810,89	4340	
132200	0,172	16,4	50	120	2973,94	1752,41	4968,16	2927,52	8952,05	4540	
132200	0,172	18,3	50	120	3141,49	1851,14	5248,07	3092,45	9567,18	5780	
132200	0,172	31,8	50	110	4141,18	2440,21	6847,29	4034,81	8697,44	7360	
132200	0,172	30,2	50	130	4035,66	2378,03	6801,44	4007,79	8697,44	6850	
233000	0,17	19,8	50	120	4312,86	2541,38	7204,92	4245,54	13000	5870	9070
240000	0,165	19,2	50	120	4247,58	2502,91	7095,86	4181,28	13000	6810	
240000	0,17	9,9	50	120	3095,13	1823,82	5170,61	3046,81	13000	6280	8970
240000	0,17	24,9	50	140	4908,63	2892,44	8336,00	4912,03	13000	17050	18040
240000	0,17	40,9	50	140	6291,04	3707,03	10683,65	6295,40	13000	14800	20400
230000	0,17	33,5	50	250	5573,67	3284,32	9903,09	5835,45	13000	15940	20150

Table 10. Experimental and computational results for carbon fibers applied externally to a brick wall

N	Ef, MPa	tf, mm	fm, Mpa	bf, mm	b, mm	ε _{max} , %	Experiment, N min-max		Notes	Pub- lished
1	73000	0,12	7,3	50	120	2,2	5250		lc=250mm, 1 experiment	[7]
2	65000	0,23	42,3	50	120	2,8	13340		lc=200mm, 1x5 experiments	[8]
3	80000	0,149	8,8	25	130	1,7	4750	4910	lc=150-200mm, 2x3 exper.	[9]
4	84251	0,12	19,8	50	120		3880	5090	lc=160mm, 6x5 experiments	[7]
5	83397	0,14	19,2	50	120	1,7	6810	4930	lc=200mm, 1x2 experiments	[11]
6	73000	0,12	7,25	50	120	1,7	10500		lc=250mm, 1x3 experiments	[1] *
7	80200	0,15	15,7	25	235		3170	5460	lc=150-200mm, 26x1 exper.	[15]

12	84251	0,12	19,8	50	120	1,69	4300	5765	lc=160mm, 5x5 experiments	[11]
*University of Sannio, internal report										

Table 11. Experimental results for glass stripes, applicated externally to masonry

Ef, MPa	tf, mm	fm, Mpa	bf, mm	b, mm	Fcnr-dt, N	Fcnr-dt,d, N	Fcnr-dt- R1, N	Fcnr-dt- R1,d, N	Faci-M, N	Experiment, N min-max	
73000	0,12	7,3	50	120	1231,53	725,68	2057,35	1212,30	3350,7	5250	
65000	0,23	42,3	50	120	3872,77	2282,05	6469,71	3812,31	5718,38	13340	
80000	0,149	8,8	25	130	788,64	464,71	1404,45	827,58	2279,7	4750	4910
84251	0,12	19,8	50	120	2178,92	1283,94	3640,03	2144,91	3867,12	3880	5090
83397	0,14	19,2	50	120	2306,39	1359,06	3852,98	2270,39	4465,91	6810	4930
73000	0,12	7,25	50	120	1227,30	723,20	2050,29	1208,14	3350,7	10500	
80200	0,15	15,7	25	235	1058,24	623,57	1934,65	1140,00	2300,74	3170	5460
84251	0,12	19,8	50	120	2178,92	1283,94	3640,03	2144,91	3867,12	4300	5765

Table 12. Ezperimental and calculation results for glass stripes, applicated external to masonry

4. Conclusions

If we accept the experimental results for 1, then we obtain the following values for the theoretically obtained:

N	Fcnr-dt, N	Fcnr-dt- R1, N	Faci-M, N
1	0,32	0,54	1,04
2	0,38	0,62	1,25
3	0,43	0,68	1,42
4	0,20	0,34	1,00
5	0,16	0,27	0,55
6	0,34	0,57	0,71
7	0,26	0,47	1,11
8	0,63	1,06	1,97
9	0,54	0,91	1,66
10	0,56	0,93	1,18
11	0,59	0,99	1,27
13	0,73	1,23	2,21

14	0,62	1,04	1,91
15	0,49	0,82	2,07
16	0,29	0,49	0,76
17	0,43	0,72	0,88
18	0,35	0,62	0,82

Table 13. Comparison of theoretical and experimental results for carbon fibers applicatedexternally to a brick wall

N	F_{cnr-dt}, N	F_{cnr-dt-R1}, N	F_{aci-M}, N
1	0,23	0,39	0,64
2	0,29	0,48	0,43
3	0,17	0,30	0,48
4	0,56	0,94	1,00
5	0,34	0,57	0,66
6	0,12	0,20	0,32
7	0,33	0,61	0,73
8	0,51	0,85	0,90

Table 14. Comparison of theoretical and experimental results for glass stripes, applicated externally to masonry

Based on the comparative analysis of experimental and theoretical results, the following Conclusions can be made:

The results obtained in the first edition of the CNR-DT 200 are very conservative and differ significantly from the experiments.

The results obtained in the second edition of the CNR-DT 200 / R1 are closer to the truth and in almost all cases in favor of security. As they often turn out to be quite conservative, it would be economically advantageous to use the "design by testing" approach at larger sites to reduce the amount of reinforcement input.

The American standards ACI440.7R-10 give the closest to the experimental results, although the computational setup is incomparably simpler and takes into account much less input data. The problem is that often the results obtained are not in favor of security.

As a Conclusion, it can be said that the CNR-DT 200 / R1 turned out to be the most detailed and with the most reliable results.

5. Anchoring length

The dissertation describes some features and made some models related to the length of voltage transmission. Of course, on a model this length is less than the calculated one, because the real construction has imperfections.

In conclusion, it can be concluded that the modulus of elasticity of the adhesive layer affects the length of stress transmission, although this is not reported in any of the regulations.

V. Determination of stiffness in the plane of a FRP strengthened masonry wall

Short description of the chapter

In this chapter are discussed:

- 1. Description of the problem*
- 2. Determination of the reduced center of gravity of a strengthened wall with a certain length of the compression zone*
- 3. Determination of the reduced moment of inertia of the strengthened wall*
- 4. Coefficient of modification of stiffness in software product*
- 5. Spreadsheet in Microsoft Excel*

In order to be able to properly model a wall strengthened by FRP strips, its rigidity must be known. This chapter derives formulas for modifying stiffness in a software product, provided that the wall is strengthened with evenly spaced strips of FRP.

1. Description of the problem

The problem of the stiffness of a masonry wall in its plane, reinforced with vertical and horizontal stripes of FRP is one of the tasks we set ourselves. This stiffness serves to more accurately determine the self-oscillation periods (although it is difficult to speak of good accuracy in masonry structures), to determine the horizontal displacements of the building and so on.

The task is complex due to several factors:

- the participation of masonry is excluded from work in a tension zone
- the participation of vertical FRP strips is excluded from work in the pressure zone

A description of a similar problem with reinforced concrete sections (meaning the exclusion of concrete in the tensile zone, not reinforcement) is in [Ivanchev, I. Design of reinforced concrete bridges according to Eurocode 2. ISBN 954-8873-97-3]

If the problem of switching off the masonry during tensile operation is similar to that of reinforced concrete elements, then switching off the FRP pressure strips is a specific problem. Its difficulty comes down to the fact that a general formula should cover first how many of these strips will "work" at a given pressure zone height and secondly their contribution should be covered in a formula convenient for computer analysis (if possible to avoid cycles for easier integration into Microsoft Excel, for example).

We will look at a wall strengthened by vertical strips of FRP at equal distances, the strips facing each other. Longitudinal compression deformations due to in the time of application of FRP

are considered to be negligibly small. We believe that the horizontal strips of FRP are dimensioned to ensure shear forces destruction.

Schematically, the problem is presented in the figure:

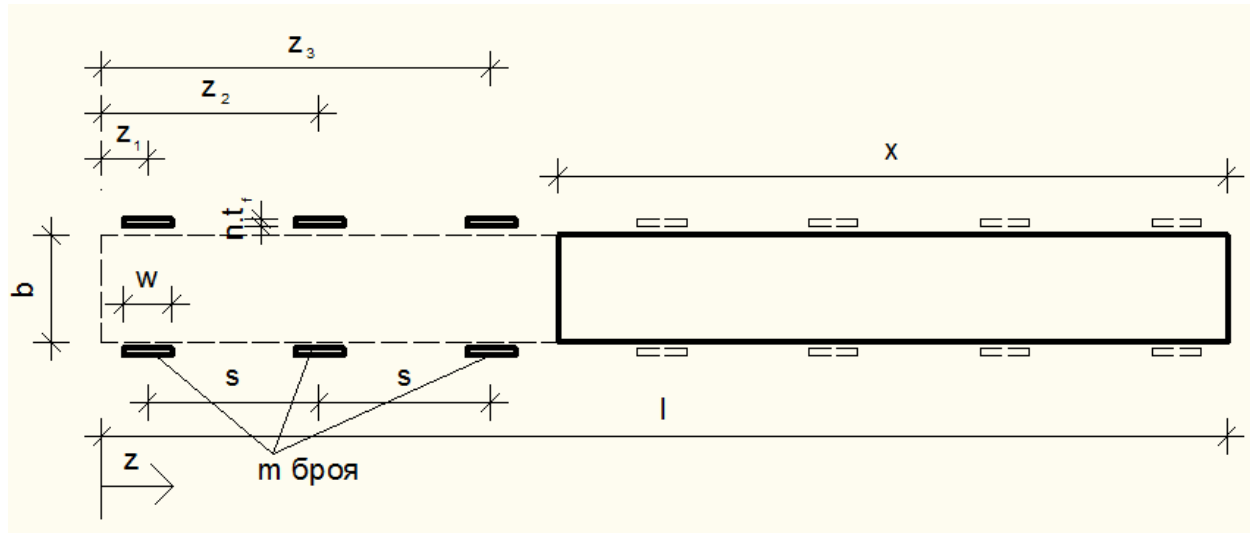


Fig. 50. Indications for the stiffness in the plane of a wall problem

The following notations are used (for short, the index "f", which is usually used for notations related to the FRP system, is omitted):

w is the width of the FRP strips

s - axial distance between FRP strips

n - number of layers of FRP laid on top of each other on one side of the wall

t_f - nominal thickness of one FRP layer

E_f - modulus of elasticity of FRP

E_b - modulus of elasticity of masonry

b - width of the wall

l - length of the wall

z_1 - distance from the tensioned end of the wall to the axis of the first vertical strip of FRP

z_i - distance from the tensioned end of the wall to the axis of the i -th vertical strip of FRP

m - number of stretched FRP strips

x - height of the compression zone

2. Determination of the reduced center of gravity of a strengthened wall with a certain length of the compression zone

The thickness of the two FRP layers facing each other is:

$$t^* = t_f \cdot n \cdot 2$$

The reduced thickness reduced to the brick wall material is:

$$t = t_f \cdot n \cdot 2 \cdot E_f / E_b$$

The coordinate of the mass center relative to the tensioned edge of the wall is:

$$z_c = \frac{\sum A_i \cdot z_i}{\sum A_i} = \frac{\sum_{i=1}^m t \cdot w \cdot z_i + x \cdot b \cdot \left(l - \frac{x}{2}\right)}{\sum_{i=1}^m t \cdot w + x \cdot b}$$

First, let's determine the number of tensioned FRP stripes m .

$$m = \text{roundup}\left(\frac{l - x - z_1}{s}; 0\right)$$

where roundup is an operator to derive the result of the division, rounded up, and the number of decimal places indicated after ";", in this case 0 means an integer.

Hence, let's keep in mind that amounts can be presented without using a cyclic algorithm in a program:

$$\sum_{i=1}^m t \cdot w \cdot z_i = t \cdot w \cdot \sum_{i=1}^m z_i$$

Considering that:

$$z_2 = z_1 + 1s, z_3 = z_1 + 2s, z_4 = z_1 + 3s, \dots$$

we can write the general formula that

$$z_n = z_1 + (n-1) \cdot s$$

So

$$t \cdot w \cdot \sum_{i=1}^m z_i = t \cdot w \cdot \left(m \cdot z_1 + s \cdot \sum_{i=1}^{m-1} i\right)$$

Using the Gaussian sum:

$$\sum_{i=1}^{m-1} i = 1 + 2 + 3 + \dots + (m-1) = \frac{1 + (m-1)}{2} (m-1) = \frac{m(m-1)}{2}$$

We find that

$$t.w. \left(m.z_1 + s. \sum_{i=1}^{m-1} i \right) = t.w. \left(m.z_1 + \frac{m(m-1)}{2} \right)$$

The second sum of the expression for the mass center is:

$$\sum_{i=1}^m t.w = m.t.w$$

So for the mass center we find:

$$z_c = \frac{t.w. \left(m.z_1 + \frac{m(m-1)}{2} \right) + x.b. \left(l - \frac{x}{2} \right)}{m.t.w + x.b}$$

This is now an easy-to-use expression, including the exclusion of tension (for masonry) and pressure (for FRP), working for any wall.

3. Determination of the reduced moment of inertia of the strengthened wall

The reduced moment of inertia with respect to an axis perpendicular to the longitudinal axis of the wall and passing through the mass center is:

$$I = \frac{b.x^3}{12} + b.x. \left(l - \frac{x}{2} - z_c \right)^2 + \sum_{i=1}^m t.w(z_c - z_i)^2$$

Similar to the previous point, let's try to express the sum so that we do not have to use cyclic algorithms.

$$\sum_{i=1}^m t.w(z_c - z_i)^2 = t.w \sum_{i=1}^m (z_c - z_i)^2$$

$$\sum_{i=1}^m (z_c - z_i)^2 = (z_c - z_1)^2 + (z_c - z_2)^2 + \dots + (z_c - z_m)^2$$

$$z_2 = z_1 + 1s, z_3 = z_1 + 2s, z_4 = z_1 + 3s, \dots, z_m = z_1 + (m-1)s$$

So

$$\sum_{i=1}^m (z_c - z_i)^2 = (z_c - z_1)^2 + (z_c - z_1 - s)^2 + \dots + (z_c - z_1 - (m-1)s)^2$$

I we take into account that

$$(z_c - z_1 - ns)^2 = (z_c - z_1)^2 - 2 \cdot (z_c - z_1) \cdot ns + (ns)^2$$

We find

$$\begin{aligned} \sum_{i=1}^m (z_c - z_i)^2 &= m \cdot (z_c - z_1)^2 - 2 \cdot (z_c - z_1) \cdot (s + 2s + 3s + \dots + (m-1)s) \\ &\quad + (1^2 + 2^2 + 3^2 + \dots + (m-1)^2) \cdot s^2 \end{aligned}$$

$$\sum_{i=1}^m (z_c - z_i)^2 = m \cdot (z_c - z_1)^2 - 2 \cdot (z_c - z_1) \cdot s \cdot \sum_{i=1}^{m-1} i + s^2 \sum_{i=1}^{m-1} i^2$$

We will present the first sum as a Gaussian sum:

$$\sum_{i=1}^{m-1} i = 1 + 2 + 3 + \dots + (m-1) = \frac{m(m-1)}{2}$$

For the development of the second sum we will use the familiar formula [Milkoeva, B., Mathematical reference book with formulas, graphs, tables and drawings in elementary mathematics, (ISBN: 9549034216)]:

$$1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n(n+1)(2n+1)}{6}$$

Therefore

$$\sum_{i=1}^{m-1} i^2 = 1^2 + 2^2 + \dots + (m-1)^2 = \frac{(m-1)(m-1+1)(2(m-1)+1)}{6} = \frac{m(m-1)(2m-1)}{6}$$

Therefore

$$\sum_{i=1}^{m-1} (z_c - z_i)^2 = m(z_c - z_1)^2 - 2 \cdot (z_c - z_1) \cdot s \cdot \frac{m \cdot (m-1)}{2} + s^2 \cdot \frac{m \cdot (m-1) \cdot (2m-1)}{6}$$

For the moment of inertia we find:

$$I = \frac{b \cdot x^3}{12} + b \cdot x \left(l - \frac{x}{2} - z_c \right) + t \cdot w (m(z_c - z_1)^2 - 2(z_c - z_1) \cdot s \cdot \frac{m(m-1)}{2} + s^2 \cdot \frac{m(m-1)(2m-1)}{6})$$

4. Coefficient of modification of stiffness in software product

If the wall is modeled as a homogeneous section with stiffness characteristics of masonry, the bending stiffness in the plane changes by a factor

$$k = \frac{I}{I_b} = \frac{I \cdot 12}{b \cdot l^3}$$

5. Spreadsheet in Microsoft Excel

For the purposes of the dissertation, a spreadsheet in Microsoft Excel environment has been compiled, which can be used for practical purposes.

VI. Dimensioning the strengthening with FRP. Procedure.

Conclusions

Short description of the chapter

In this chapter are discussed:

1. General statements

2. Load-bearing capacity of a wall, strengthened with FRP materials in its plane.

Interactional diagram

3. . Chart table in Microsoft Excel environment

One of the most convenient ways to design in compression and bending moment of masonry walls strengthened with vertical strips of FRP is to use an interactional diagram. Formulas have been developed by which such a diagram can be drawn, the wall is strengthened by evenly distributed strips of FRP. A table has been created in Microsoft Excel environment for practical application.

1. General statements

Standards [CNR DT 200/2004] and [ACI440.7R-10 Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures] set out general guidelines for dimensioning reinforced masonry walls with FRP materials in and out of their plane. The aim of this chapter of the dissertation is to develop a procedure for dimensioning masonry walls strengthened by FRP. This finds various applications in real practice, for example in the case of seismic reinforcement of masonry structures, it is important to determine the load-bearing capacity in the plane of the brick wall, acting as a shear wall.

Some basic statements are given in [Benedetti, Andrea & Steli, Elisa. (2008). Analytical models for shear–displacement curves of unreinforced and FRP reinforced masonry panels. Construction and Building Materials - CONSTR BUILD MATER. 22. 175-185. 10.1016/j.conbuildmat.2006.09.005.].

2. Load-bearing capacity of a wall, strengthened with FRP materials in its plane.

Interactional diagram

The main principles for testing the load-bearing capacity of a wall strengthened with vertical strips of FRP for bending moment and normal force are given in Chapter 3.

One of the ways to study eccentrically compressed and eccentrically tensioned elements, which has gained popularity recently and illustrates the load-bearing capacity of the section, especially if it needs to be tested for several pairs of torque and normal force, is the interactional diagram.

The peculiarities of constructing an interaction diagram of a masonry wall strengthened by FRP materials, compared to a reinforced concrete wall, are the following

- FRP fabric has a perfectly linear-elastic stress-strain relationship, unlike reinforcement, which has a yielding horizontal part
- the procedure must be such as to calculate the admissible deformations in FRP, because they depend on the type of fibers and the characteristics of the reinforced wall
- the procedure must be such that it takes into account when the FRP strip is pressed
- at each iteration to determine the number of stretched and pressed strips and to exclude from work the pressed
- to determine the number of strips itself, ie to be able to work on any wall with a set distance between the strips
- since the FRP strips are not placed as the reinforcement - in zero stress state, the procedure must take into account the stresses in the wall during the installation of FRP - the wall will be pressed at least with a vertical load. Usually these stresses can be assumed to be evenly distributed
- An additional feature is the determination of the allowable effort when no strip has "worked", ie. the cross section is eccentrically pressed with the result in the core - this problem is not related to the problem of reinforcement with FRP, but is important for determining the load-bearing capacity of the existing wall and the need for reinforcement in another way

Procedure for drawing an interactional diagram for a reinforced concrete wall is given in [Milev, J, V. Kardzhiev, Design of reinforced concrete structures according to Eurocode 8, ISBN 987-954-92274-3-11], guidelines for drawing an interactional diagram of material which does not allow tension are given in [Simple Method for the Design of Jet Grouted Umbrellas in Tunneling, Gian Piero Lignola, Gaetano Manfredi, Journal of Geotechnical and Geoenvironmental Engineering 134(12):1778-1790 · December 2008]

Based on these guidelines, a procedure for drawing an interactional diagram on a masonry wall strengthened with FRP materials will be shown.

Let's first look at an interactional diagram of a masonry wall that is not loaded with initial stresses during application of FRP strips, for example a wall on the top floor of a building with a dismantled roof or with a negligibly small load from it. We will work with the statements given in [CNR DT 200/2004 / R1].

Let's consider the case where FRPs are located at equal distances, they are the same (which is the most common case in practice), their number is arbitrary (set by the distance between them) and the wall has a rectangular cross section in plan (no contribution of the transverse wall is taken into account).

Given:

L - length of the wall

b - width of the wall

f_{mb} - average value of compressive strength of masonry

FC - coefficient of safety of masonry, determined depending on the type of masonry, according to Eurocode 6 [BDS EN 1996]

Type of fibers used for reinforcement: carbon fibers, aramid fibers, glass fibers

System type: certified system (application type A), non-certified system (application type B)

t_f - nominal thickness of one FRP layer

E_f - modulus of elasticity of FRP

w is the width of the FRP strips

s - axial distance between FRP strips

a - distance from the tensioned end of the wall to the axis of the first vertical strip of FRP

ϵ_{fk} - admissible deformations in case of FRP rupture

l_b - Anchoring length: at least the required or below the required size

Wanted:

Interactive M-N diagram of the bearing capacity of the section.

Additional indications:

n - number of tensioned FRP strips

x - height of the compression zone

ϵ_c – strain in the compressed edge

ϵ_t – strain in the most tensioned FRP strip

ϵ_{fd} – limit strain in the FRP strips

l_e – necessary anchoring length

1. Determination of admissible strains in FRP strips

The procedure described in Chapter 3 determines the following:

η_a and γ_f are determined depending on the type of system

$$\Gamma_{fd} = \frac{k_b \cdot k_c}{FC} \cdot \sqrt{f_{mb} \cdot f_{btm}}$$

f_{btm} – tension strength of the masonry, according to [CNR DT 2000/2004/R1] може да се it can be taken $0,1 \cdot f_{mb}$

FC – safety factor, as it is a question of strengthening a brick wall, it is logical to accept the coefficient γ_M from Eurocode 6, although the necessary specifics are not given.

k_b – coefficient taking into account the geometry

$$k_b = \sqrt{\frac{3 - b_f/b}{1 + b_f/b}}$$

where b is the width of the strengthened element, if it is larger than 1 brick, to the end of the brick on which the FRP strip is attached, b_f is clarified above.

$$l_e = \max \left\{ \frac{1}{\gamma_{Rd} \cdot f_{bd}} \sqrt{\frac{\pi^2 \cdot E_f \cdot t_f \cdot \Gamma_{fk}}{2}}; 150mm \right\}$$

$\gamma_{Rd} = 1,25$ for brick masonry

$$f_{fdd} = if(l_b = l_e; \frac{1}{\gamma_{fd}} \cdot \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{fd}}{t_f}}; \left(\frac{1}{\gamma_{fd}} \cdot \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{fd}}{t_f}} \right) * \frac{l_b}{l_e} \left(2 - \frac{l_b}{l_e} \right))$$

Where the operator for conditional algorithm is if (condition; action, if the condition is fulfilled; action if the condition is not fulfilled)

$$\varepsilon_{fdd} = \frac{f_{fdd}}{E_f}$$

$$\varepsilon_{fd} = \min \left\{ \eta_a \frac{\varepsilon_{fk}}{\gamma_f}; \varepsilon_{fdd} \right\}$$

The picture of deformations and stresses in case part of the section is compressed, ie. the height of the compression zone x is between 0 and L, where L is the length of the wall, is as follows:

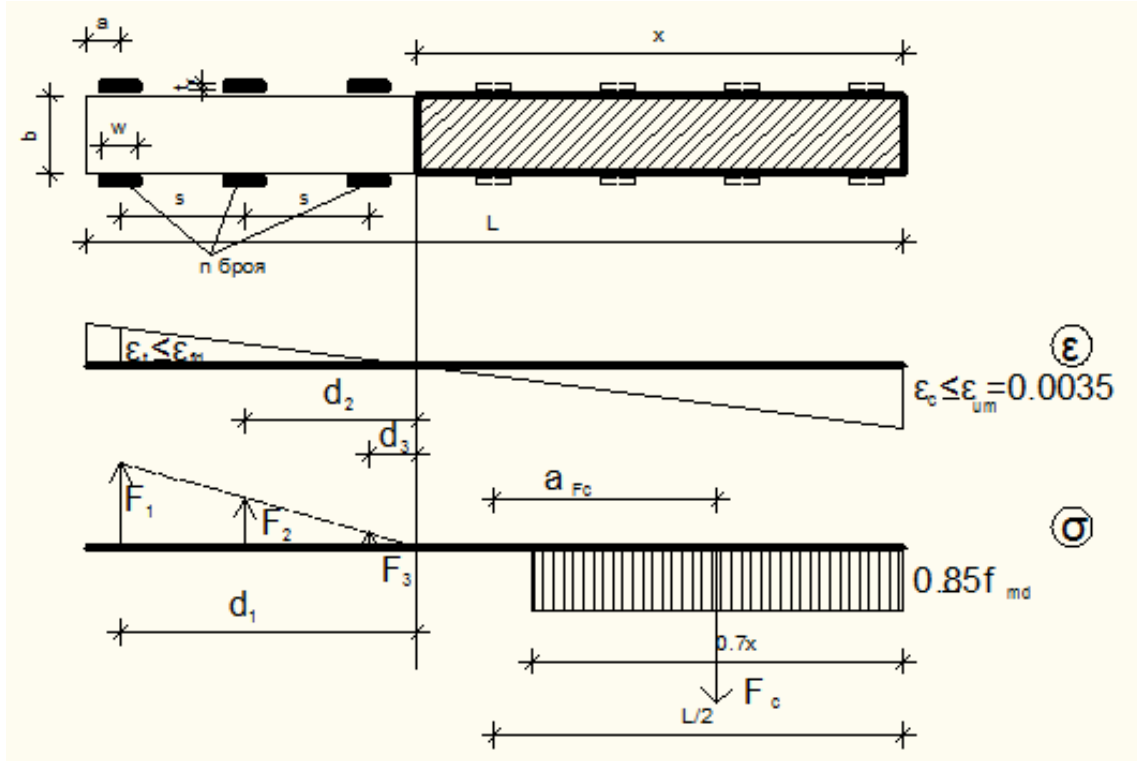


Fig. 51. Indications

Let us first determine the deformations at arbitrary x :

$$\varepsilon_c = \begin{cases} \varepsilon_{fd} * \frac{x}{L - a - x}, & \text{ако } \varepsilon_{mu} * \frac{L - a1 - x}{x} > \varepsilon_{fd} \\ \varepsilon_{mu}, & \text{ако } \varepsilon_{mu} * \frac{L - a1 - x}{x} \leq \varepsilon_{fd} \end{cases}$$

$$\varepsilon_t = \begin{cases} \varepsilon_{fd}, & \text{ако } \varepsilon_{mu} * \frac{L - a1 - x}{x} > \varepsilon_{fd} \\ \varepsilon_{mu} * \frac{x}{L - a - x}, & \text{ако } \varepsilon_{mu} * \frac{L - a1 - x}{x} \leq \varepsilon_{fd} \end{cases}$$

The number of "working" FRP strips is:

$$n = \text{roundup}\left(\frac{L - x - a}{s}; 0\right)$$

The resultant force of the compression stresses in the masonry wall is::

$$F_c = \frac{0,85 \cdot f_{mk} \cdot b \cdot 0,7 \cdot x}{\gamma_M}$$

The distance from the application point of the resultant of the forces in the compression zone to the mass center of the wall is:

$$a_{Fc} = \frac{l}{2} - 0.35x$$

The tension force in every FRP strip is:

$$F_i = t_f \cdot w \cdot E_f \cdot \varepsilon_i$$

The strains in every FRP :

$$\varepsilon_i = \varepsilon_t \cdot \frac{d_i}{L - x - a}$$

The resultant force for all FRP stripes is:

$$F_t = \sum_{i=1}^n 2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t \cdot \frac{d_i}{L - x - a}$$

Where the multiplication by 2 takes into account, that there are FRP strips in both wall faces.
When we put all the constants before the sum:

$$F_t = \frac{t_f \cdot w \cdot E_f \cdot \varepsilon_t}{L - x - a} \sum_{i=1}^n d_i$$

The sum $\sum_{i=1}^n d_i$ can be presented this way:

$$\begin{aligned} \sum_{i=1}^n d_i &= (L - x - a) + (L - x - a - s) + (L - x - a - 2s) + \dots + (L - x - a - n \cdot s) \\ &= n \cdot (L - x - a) - s \cdot \sum_{i=1}^{n-1} i \end{aligned}$$

If we use Ghauss sum:

$$\sum_{i=1}^{n-1} i = 1 + 2 + 3 + \dots + (n-1) = \frac{1 + (n-1)}{2} (n-1) = \frac{n(n-1)}{2}$$

We find:

$$\sum_{i=1}^n d_i = n \cdot (L - x - a) - s \cdot \frac{n(n-1)}{2}$$

The resultant force in all tensioned FRP strips is:

$$F_t = \frac{2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t}{L - x - a} \cdot \left(n \cdot (L - x - a) - s \cdot \frac{n(n-1)}{2} \right)$$

The bending moment capacity of the section is:

$$M = F_c \cdot a_{Fc} + \sum_{i=1}^n F_i \cdot \left(d_i - \left(\frac{L}{2} - x \right) \right)$$

The sum is:

$$\begin{aligned} \sum_{i=1}^n F_i \cdot \left(d_i - \left(\frac{L}{2} - x \right) \right) &= \sum_{i=1}^n \left(2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t \cdot \frac{d_i}{L - x - a} \right) \cdot \left(d_i - \frac{L}{2} + x \right) \\ &= \frac{2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t}{L - x - a} \sum_{i=1}^n d_i \cdot \left(d_i - \frac{L}{2} + x \right) \end{aligned}$$

After some calculations:

$$\sum_{i=1}^n d_i \cdot \left(d_i - \frac{L}{2} + x \right) = \sum_{i=1}^n \left(d_i^2 + \left(-\frac{L}{2} + x \right) d_i \right) = \sum_{i=1}^n d_i^2 + \left(-\frac{L}{2} + x \right) \sum_{i=1}^n d_i$$

The same way like in Chapter 5 we present the sum:

$$\begin{aligned}
 \sum_{i=1}^n d_i^2 &= (L - x - a)^2 + (L - x - a - s)^2 + (L - x - a - 2s)^2 + \dots + (L - x - a - n \cdot s)^2 \\
 &= (L - x - a)^2 + (L - x - a)^2 - 2(L - x - a)s + s^2 + (L - x - a)^2 \\
 &\quad - 2(L - x - a) \cdot 2s + (2s)^2 + \dots + (L - x - a)^2 - 2(L - x - a) \cdot ns + (n \cdot s)^2
 \end{aligned}$$

Shortly:

$$\begin{aligned}
 \sum_{i=1}^n d_i^2 &= \sum_{i=1}^n (L - x - a)^2 - \sum_{i=1}^{n-1} 2(L - x - a) \cdot is + \sum_{i=1}^{n-1} (i \cdot s)^2 = n \cdot (L - x - a)^2 \\
 &\quad - 2(L - x - a) \cdot s \sum_{i=1}^{n-1} i + s^2 \sum_{i=1}^{n-1} i^2
 \end{aligned}$$

We make it more simple:

$$\sum_{i=1}^{n-1} i = 1 + 2 + 3 + \dots + (n - 1) = \frac{1 + (n - 1)}{2} (n - 1) = \frac{n(n - 1)}{2}$$

$$\sum_{i=1}^{n-1} i^2 = 1^2 + 2^2 + \dots + (n - 1)^2 = \frac{(n - 1)(n - 1 + 1)(2(n - 1) + 1)}{6} = \frac{n(n - 1)(2n - 1)}{6}$$

We find

$$\sum_{i=1}^n d_i^2 = n \cdot (L - x - a)^2 - 2(L - x - a) \cdot s \cdot \frac{n(n - 1)}{2} + s^2 \cdot \frac{n(n - 1)(2n - 1)}{6}$$

In the end we find:

$$M = F_c \cdot a_{Fc} + \frac{2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t}{L - x - a} \left(\sum_{i=1}^n d_i^2 + \left(-\frac{L}{2} + x \right) \sum_{i=1}^n d_i \right)$$

$$\begin{aligned}
 M &= F_c \cdot a_{Fc} + \frac{2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_t}{L - x - a} \left(n \cdot (L - x - a)^2 - 2(L - x - a) \cdot s \cdot \frac{n(n - 1)}{2} + s^2 \cdot \frac{n(n - 1)(2n - 1)}{6} \right. \\
 &\quad \left. + \left(-\frac{L}{2} + x \right) \left(n \cdot (L - x - a) - s \cdot \frac{n(n - 1)}{2} \right) \right)
 \end{aligned}$$

The normal force in the section is:

$$N = F_t - F_c$$

Particular points in the construction of the interaction diagram are the following:

$$x = 0$$

Then there is no pressure zone, the whole section is tensioned. The tensile force and the bending moment are obtained from the above formulas by replacing x with 0.

$$x = -\infty$$

Here the whole section is tensioned evenly. The tensile force is:

$$F_t = 2 \cdot t_f \cdot w \cdot E_f \cdot \varepsilon_{fd} \cdot n$$

where n is the total number of FRP bands. The bending moment is equal to 0.

For the purposes of the dissertation, a table in Microsoft Excel environment has been developed, which works according to the given formulas.

If it is necessary to take into account the initial deformations in the masonry when gluing FRP, proceed as follows. Again, the same distance values set for the compression zone x are used, which are fictitious values here. The real values are obtained from the fictitious ones by the following considerations.

The permissible deformations in FRP do not depend on the initial stresses, so reaching the limit state due to tensile deformations will be at the same value. But the picture of compressive stresses will be different, because there will be areas where we will have both tensile stresses in FRP and compressive stresses in the wall. A view of the stress and strain state is given in the following figures.

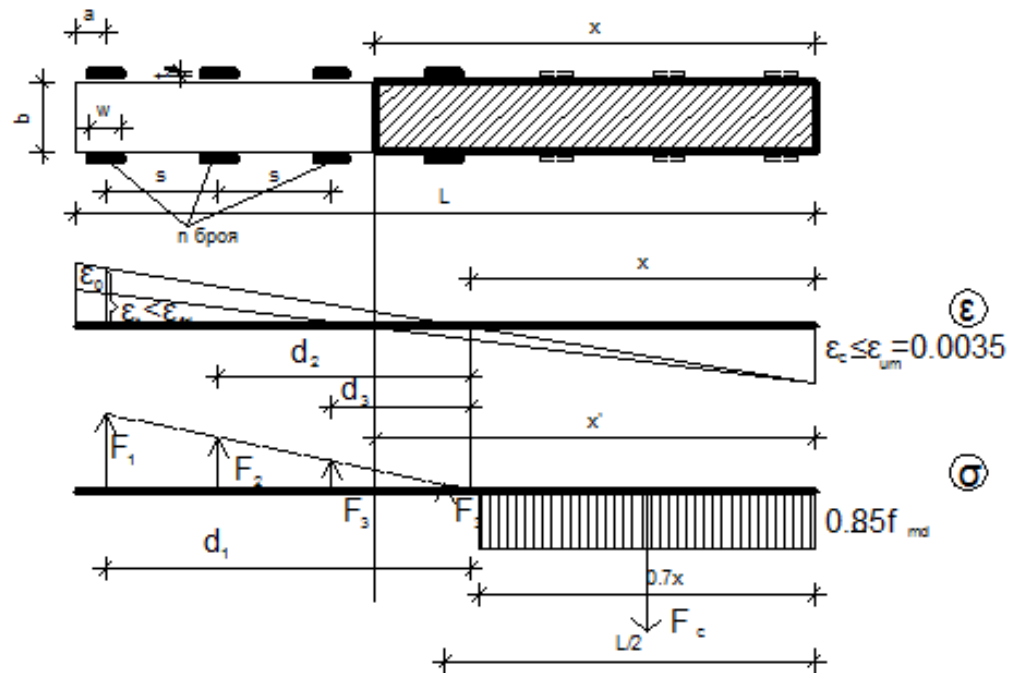


Fig. 52. Stresses and strains in a wall strengthened by FRP strips at initial compressive stresses in the wall, less than the allowable tensile stresses in FRP

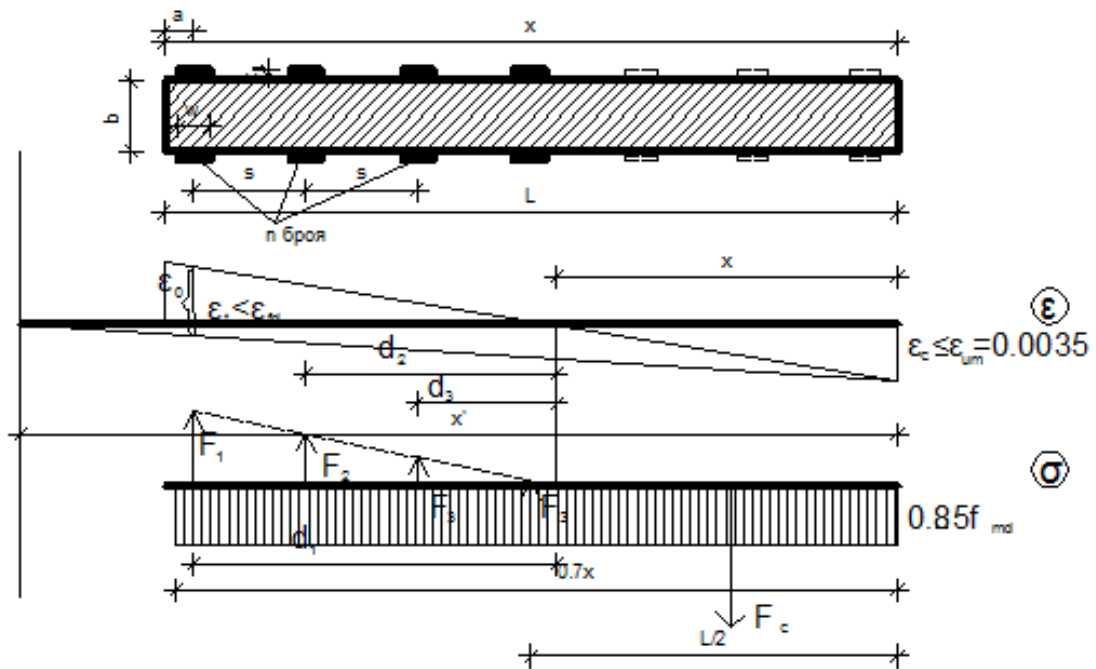


Fig. 53. Stresses and strains in a wall strengthened by FRP strips at initial compressive stresses in the wall, greater than the allowable tensile stresses in FRP

In both cases, shown in both figures, the determination of the actual length of the pressure zone relative to the fictitious one is done with similar triangles.

Additional indications:

σ_0 - initial voltage in the wall, accepted as evenly distributed

ε_0 - initial deformation

x' - actual length of the compression zone

$$x' = \frac{\varepsilon_c}{\varepsilon_c - \varepsilon_0 + \varepsilon_t} * L$$

The procedure for calculating bending moment and normal force is the same, except that the contribution of FRP strips is calculated by their deformations (can be said with the fictitious pressure zone x), and the brick wall - with the actual height of the pressure zone x' .

3. . Chart table in Microsoft Excel environment

Моделиране и изследване поведението на усилени строителни конструкции

For the purposes of the dissertation, a spreadsheet has been developed, drawing an interaction diagram that can be used for practical work.

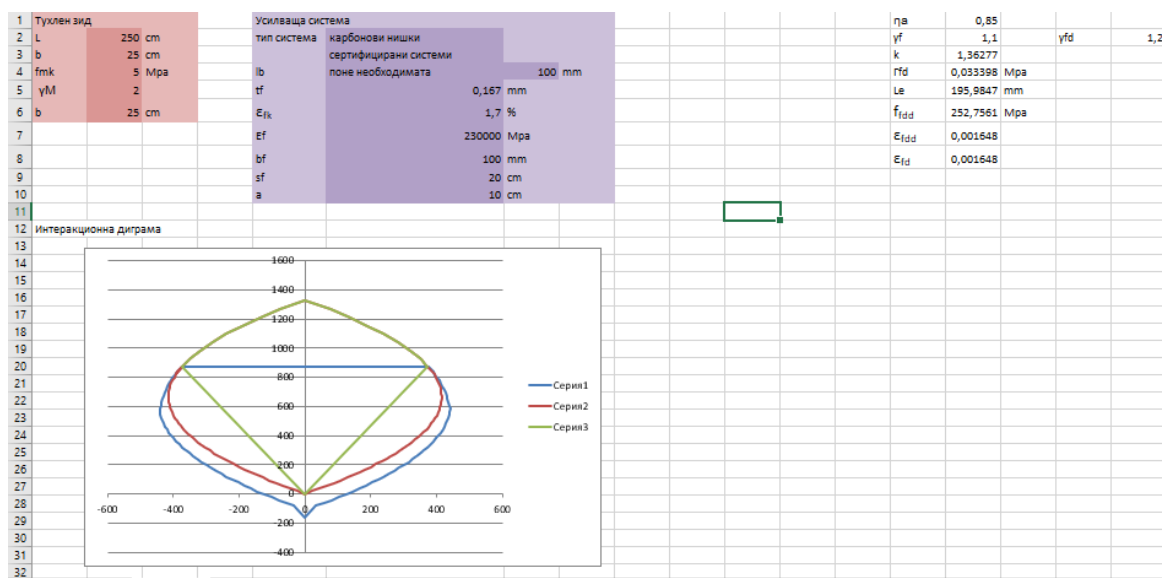


Fig. 54. Table in Microsoft Excel environment

VII. Program for drawing an interactional diagram

Short description of the chapter:

In this chapter are discussed:

- 1. General provisions*
- 2. Program overview and input*
- 3. Output*
- 4. Algorithm*

A computer program on the Lazarus platform has been created, which draws an interactional diagram and determines the height of the compression zone at a given normal force (bending moment is the maximum corresponding to it) for any wall (with widenings at the ends contributing to the compression zone) located strips of FRP (Algorithm itself works up to 6 strips, but the principle would be the same for more).

1. General provisions

The algorithm outlined in the previous chapter is very useful, but only works on a wall with a rectangular cross section (no cross walls) and evenly spaced reinforcing strips. Therefore, in this chapter we will show algorithm and its application in the Pascal programming language environment, Lazarus platform. With the help of this program, users will be able to draw an interaction diagram of a brick wall reinforced with up to 6 FRP vertical stripes (the use of more would be rare in real practice), located randomly and with different numbers of FRP strips in each strip, as and take into account the presence of transverse walls at one or both ends of the wall. It is assumed that the deformations in the wall during the bonding of FRP are small and are neglected by the subsequent redistribution of forces.

The width of the strip of transverse wall, which acts as a contributing width, is determined in accordance with the requirements of Eurocode 8 or another relevant standard by which the structure is dimensioned. In the program it is set this cooperating width by the user.

2. Program overview and input

All input and output data must be located in the program window - in this case the graph. Buttons are needed to draw the interaction diagram and to clear the diagram to make a new one in case it does not need to be compared with the previous one.

Fig. 55. View of the program with numbering of the objects for input data

Required input:

L - length of the wall, set in cm

b - width of the wall, set in cm

f_b - average value of compressive strength of bricks for masonry, set in MPa

f_m - average value of compressive strength of masonry, set in MPa

FC - coefficient of safety of masonry, determined depending on the type of masonry, according to Eurocode 6 [БДC EN 1996]

b_m - size of the brick, according to the schemes in [CNR-DR 200 / R1], set in cm

E_f - modulus of elasticity of FRP, set in MPa

b_f - width of the FRP strip, set in mm

l_e - real anchoring length, if less than the minimum, is set in mm

ϵ_{fk} - admissible deformations in case of FRP rupture, set in %

Type of fibers used for reinforcement: carbon fibers, aramid fibers, glass fibers

System type: certified system (application type A, non-certified system (application type B)

t_f - nominal thickness of one FRP layer, set in mm

d_i - distance from one end of the wall to the axis of the i -th vertical strip of FRP

n_i - number of FRP bands in the i -th vertical strip of FRP

a - size of the transverse wall, set in cm

g - transverse wall thickness, set in cm

c - size of the other transverse wall, set in cm

h - thickness of the other transverse wall, set in cm

3. Output

Interactive M N diagram of the bearing capacity of the section

For the corresponding N force, the size of the pressure zone x should be found

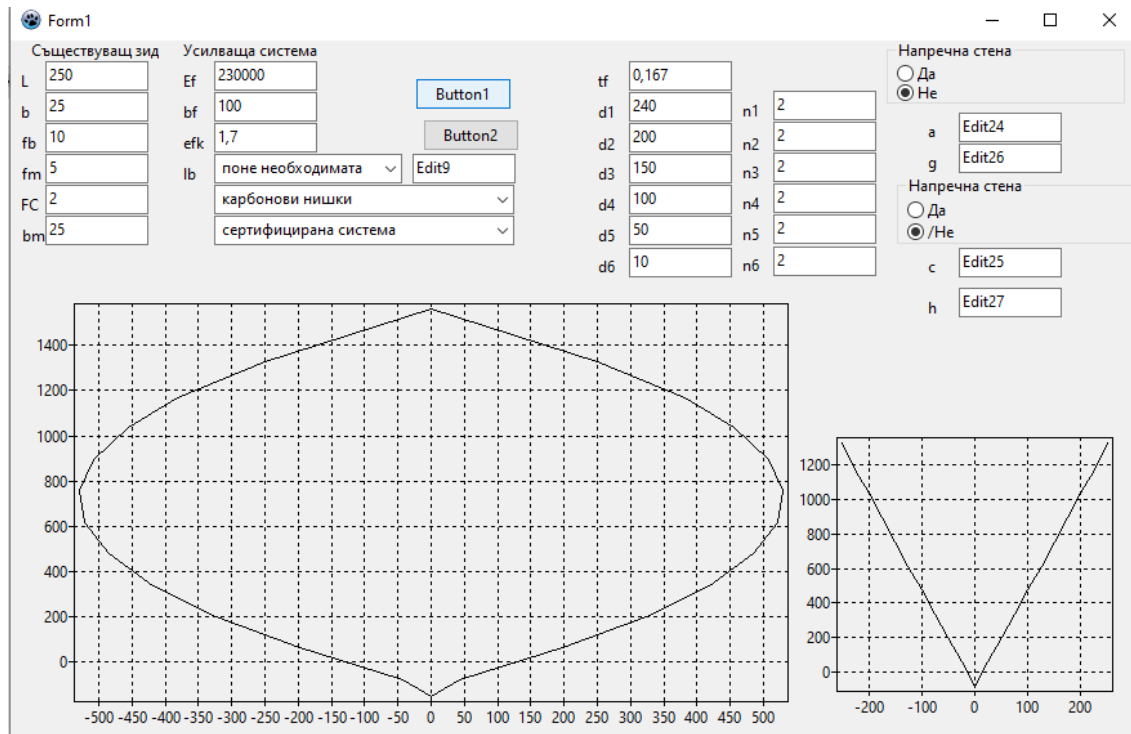


Fig. 56. View of the program – output

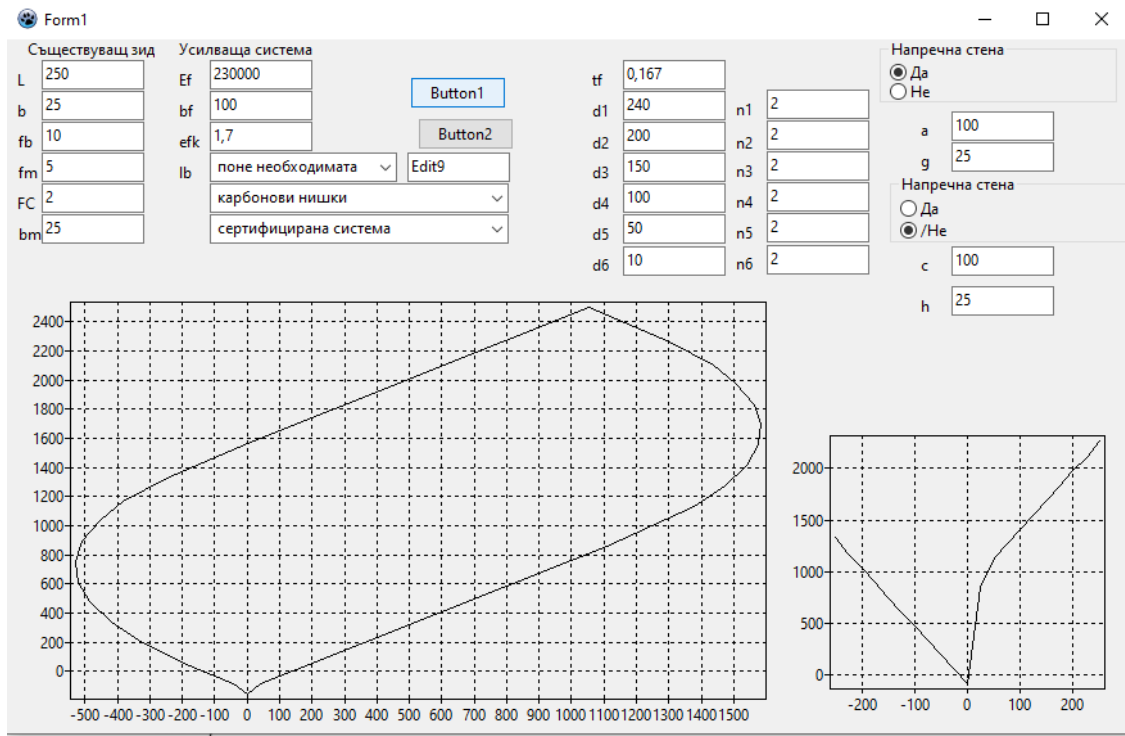


Fig. 57. Vie of the program - output

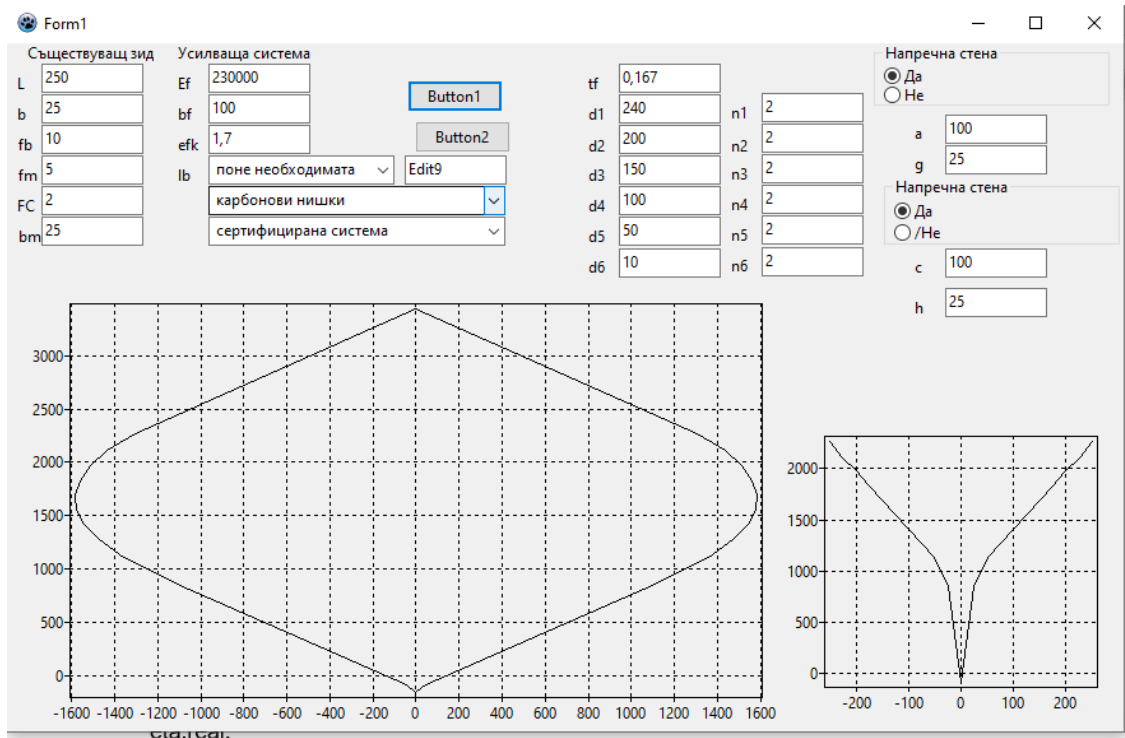


Fig. 58. View of the program - output

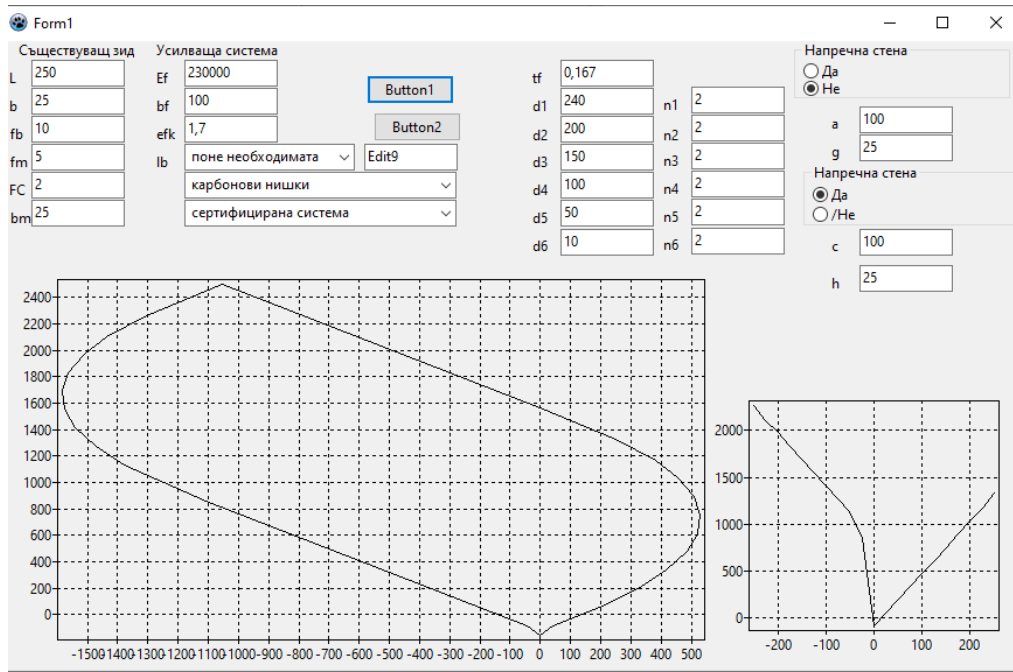


Fig. 59. View of the program - output

4. Algorithm

The algorithm of the program is presented in detail in the dissertation.

VIII. On anchoring at foundations

Short description of the chapter:

In this chapter are discussed:

1. Existing solutions
2. Anchoring proposal

1. Existing solutions

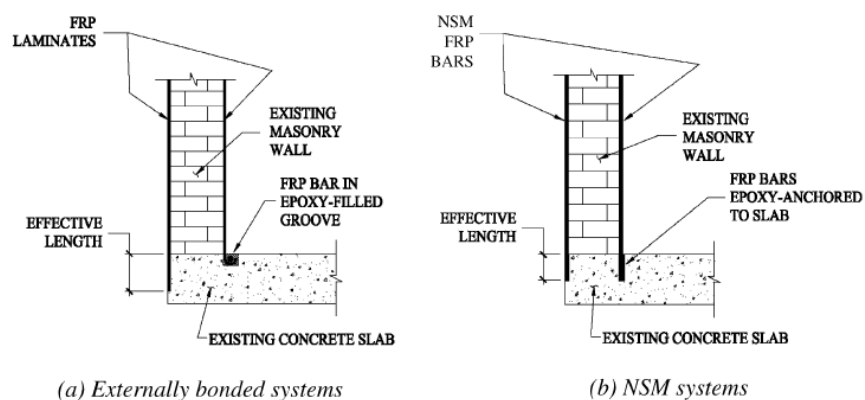


Fig.60. Anchoring in reinforced concrete element in epoxy-filled groove, shown in 'ACI

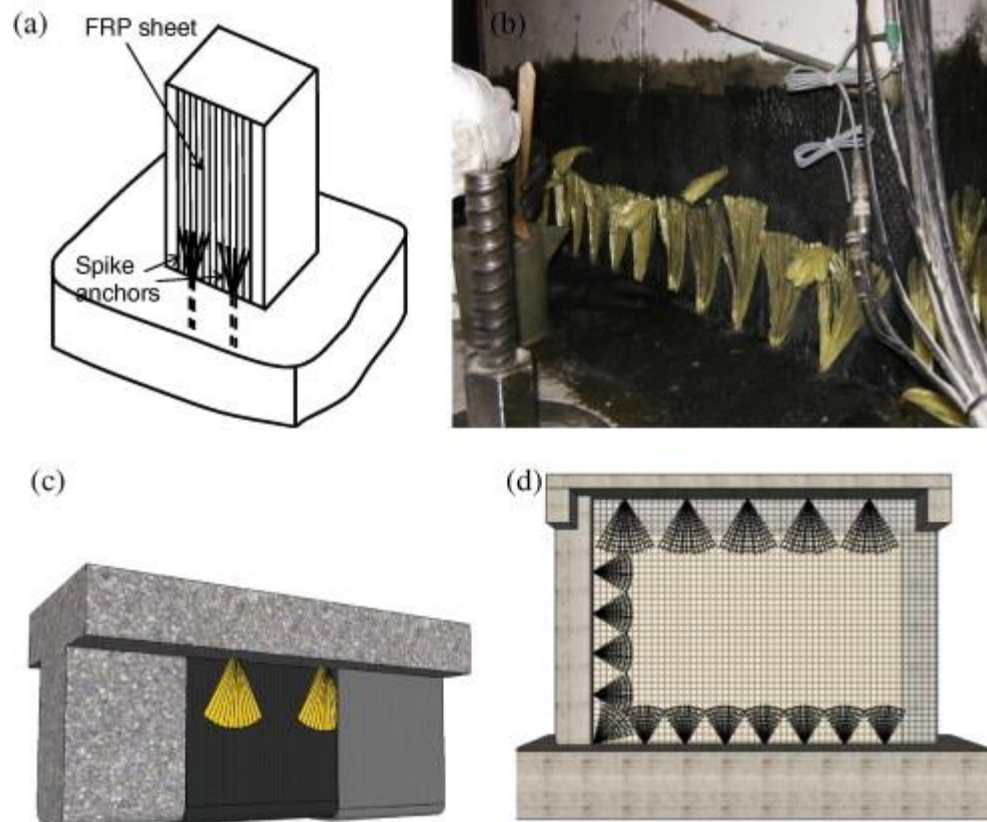


Fig.61. Anchoring with anchoring facilities

2, Anchoring proposal

mej

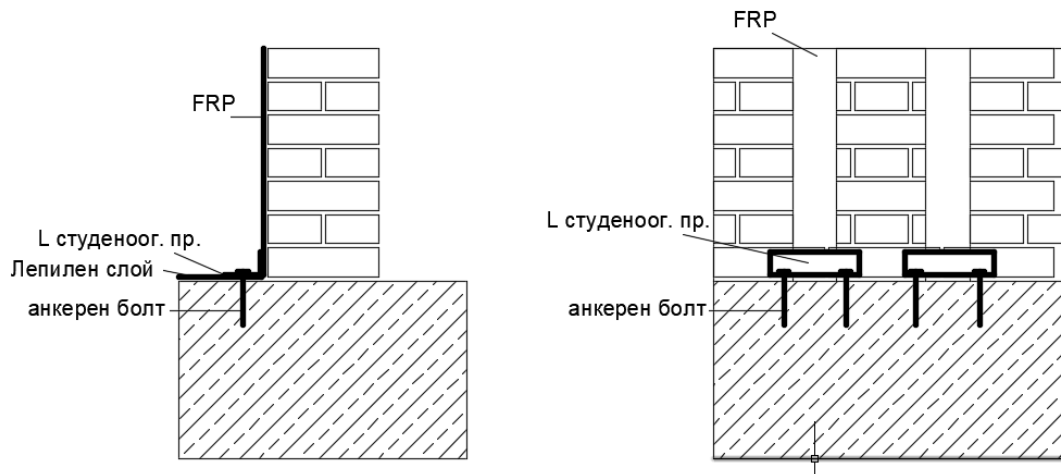


Fig.62. Anchoring proposal



Fig.63. SAP model

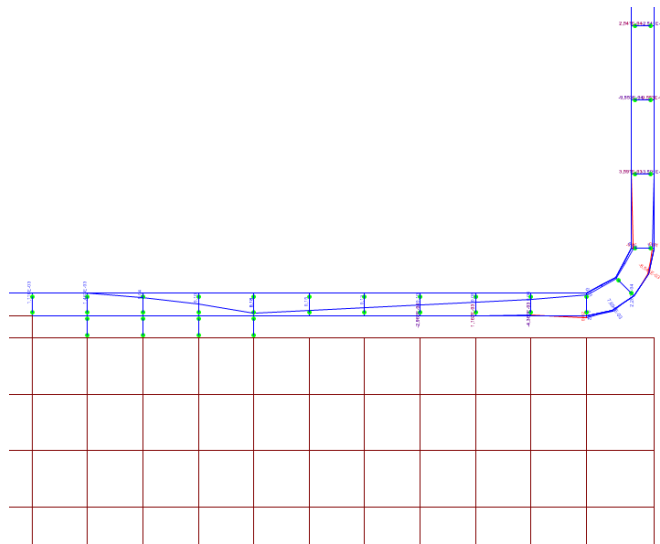


Fig.64. Bending moments

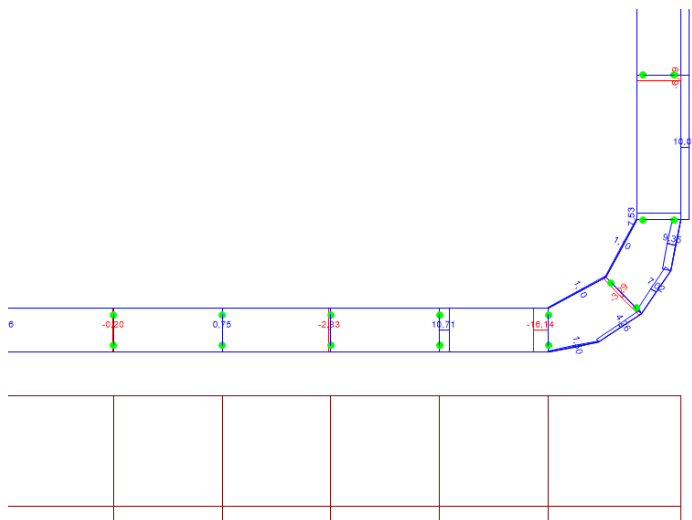


Fig..65. Normal forces

The proposed anchoring option is applicable when the foundation protrudes away from the wall (if this is not the case, the FRP strip can easily be applied directly to the foundation). The idea is to change the direction of the FRP strip with the help of a cold-bent profile, appropriately attached to the strip foundation, and to subject it to decoupling by cutting with the foundation. Peeling of the stretch strip to the surface of the foundation is prevented by the metal profile. The profile is cold-bent to have a rounded edge, not an edge to cut the FRP strip.

IX. Conclusion

We can make the following conclusions:

- The modeling of existing structures and their strengthening is a complex task. Detailed inspection of defects and damages is necessary in view of proper analysis and engineering interventions.
- Regulations are currently poorly developed in the field of evaluation and reinforcement of existing structures and therefore the role of the designer in the survey and proper interventions in the building is greater than in the design of new buildings.
- Buildings with load-bearing masonry are the most common in Bulgaria. It is possible to strengthen them with FRP stripes.
- The most common form of destruction of the strengthening system is debonding of the strips from the base. World standards in this area are few and provide different methods for determining the admissible stresses and strains. CNR-DT200-2004 / R1 is the most suitable for use, and for larger sites it may be cost-effective to design by testing because the results of this standard are conservative.
- The stiffness in the plane of a wall reinforced with FRP strips is less than that of a crack-free wall and depends on the size of the compression zone. In the dissertation algorithm is proposed to determine this stiffness.
- The dimensioning of the strengthening system is a complex task, which generally requires a cyclic Algorithm for iterations. If there are transverse walls, they should be taken into account (according to the requirements of the normative documents), because they seriously affect the interactional diagram. The dissertation proposes two algorithms, an Excel spreadsheet and a computer program to solve this problem.
- An important condition for the good operation of the reinforcing system is the correct anchoring in the foundations. In the dissertation a new variant solution is proposed.

Claims for scientific and applied contributions:

1. An overview and critical analysis of the problems of interference in existing structures in connection with:
 - Defects and damages and their modeling
 - Legislation
2. An overview of the theories and regulations for admissible deformations and stresses in FRP strips externally applied to walls has been made. They are compared with a wide range

of experiments around the world and recommendations are made to the designers for the conservatism of each of the normative documents..

3. A formula is derived and a table is created in Microsoft Excel environment for determining the stiffness in the plane of a masonry wall, strengthened with uniformly distributed and equidistant vertical strips of FRP.

4. An algorithm and a chart with diagrams in Microsoft Excel environment have been created for drawing an interactional diagram on a masonry wall, strengthened with identical, equidistant strips of FRP.

5. Algorithm and a computer program (.exe file) were created to draw an interactional M-N diagram and to determine the height of the compression zone at a given normal force (bending moment is the maximum corresponding to it) on any wall with widenings assisting in the pressure zone and random and randomly located strips of FRP.

6. A new variant detail of the connection to the foundations of a vertical strip of FRP on a wall is proposed.

List of publications on the topic of the dissertation:

1. Publications that are part of the dissertation itself

- [1] A. Gorolomov, Approaches for estimation of the need of rehabilitation of existing buildings, according to different regulations, Сборник научных статей Традиции, современные проблемы и перспективы развития строительства, Гродно, 23–24 мая 2019 года, стр. 82, ISBN 978-985-582-276-0
- [2] A. Gorolomov, Approaches for using pushover analysis for estimation of the need of rehabilitation of existing buildings, Сборник научных статей Традиции, современные проблемы и перспективы развития строительства, Гродно, 23–24 мая 2019 года, стр. 86, ISBN 978-985-582-276-0
- [3] Anton Gorolomov, Anita Handruleva, Petar Grekov, Calculation of the in-plane stiffness of a masonry wall, strengthened by vertical frp stripes, International scientific conference VSU2021, Book with proceedings ISSN: 1314-071X
- [4] A. Gorolomov, A. Handruleva, P. Grekov, Admissible stresses and strains in FRP stripes, applied to strengthen masonry elements, Annual bokk of UACEG ISSN 1310-814X, Book 55, accepted for publishing with positive remark in 04.02.2022

2. Publications related to the topic of the dissertation (assessment, restoration and strengthening of building structures), which are not an excerpt from the dissertation:

- [5] Grekov P., A. Gorolomov, D. Partov, B. Straka, R. Nikolov; „Methods for strengthening of wooden columns in preemergency state in historical structures, and choosing the one of them for reinforcement of the supporting columns in the Church “Sv. Uspenie Bogorodichno” in Kyustendil”; 11 International Conference:

- assessment, maintenance and rehabilitation of structures and settlements conference proceedings; editor: Prof. emeritus Dr Radomir Folić, Zlatibor, 19–21 June 2019, Searbija, pp.55-72.
- [6] Grekov P., D. Partov, B. Straka, M. Drdácý, I. Ivanchev, A. Gorolomov, R.Nikolov, “Timber arch system developed by ph. De l,orme and its appliction in the historic and conteporary roof structures”, 11 International Conference: assessment, maintenance and rehabilitation of structures and settlements conference proceedings); Editor: Prof. emeritus dr Radomir Folić, Zlatibor, 19– 21 June, 2019, Searbija, pp.485-502.
- [7] Grekov P., A. Gorolomov, B. Straka, D. Partov; Strengthening the damaged wooden columns after investigating of several interesting approaches from abroad”, Proceedings of International Scientific Conference VSU,2019, Sofia, 17-19, October, 2019, Topic: Mechanics and mathematics,
- [8] Grekov P., A. Gorolomov, D. Partov, B. Straka, R. Nikolov; “Accident with timber colonnade of the 200 years old church and methods for the strengthening”, Proceedings of International Scientific Conference BASA,2019, Sofia, 21-23, November, 2019, Topic 4:, Restoration of historical masonry, timber and steel structures-criteria - innovative solutions and case studies; Seismic rehabilitation of historical masonry, timber and steel structures; Conservation and preservation of historical masonry, timber and steel structures; Consolidation, rebuilding and strengthening of historic structures; Culture heritage under catastrophic events: fire, flood and blast loading, pp.301-314.
- [9] Gorolomov A., V. Georgiev, D. Partov, 110 Years History of Synagogue Construction in the Capital City Sofia in Bulgaria; Proceedings of International Scientific Conference VSU,2019, Sofia, 17-19, October, 2019, Topic: Building Structures, pp: CD.
- [10] Grekov P., A. Gorolomov, D. Partov, N. Tuleshkov, M. Drdácý and G. Pianese, „Static analysis and retrofitting of the old timber roof structures for the storage heritage building in Kustendil, Bulgaria„Proceedings of International Scientific Conference VSU, 2020, Sofia, 15-17, October, 2020, Topic: Mechanics and mathematics, pp: CD

3. Articles ready at the time of submission of the dissertation, but not yet passed the publication procedure:

- [11] Anton N. Gorolomov, Anita K. Handruleva, Petar G. Grekov, Procedure for dimensioning the bearing capacity for bending moment and axial force of a masonry wall, strengthened by FRP materials

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