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RESEARCH ON THE APPLICATION OF GEOPOLYMER CONCRETE FOR PRESTRESSED GIRDER STRUCTURES OF BRIDGES TOWARDS SUSTAINABLE DEVELOPMENT

Nguyen Binh Ha[1], *Le Ba Danh[1], Pham Duy Hoa[1], Nguyen Ngoc Tuyen[1]

[1]Department of Bridge and Tunnel Engineering, Hanoi University of Civil Engineering
55 Giai Phong, Hai Ba Trung, Hanoi, Vietnam

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ABSTRACT: In this study, geopolymer concrete is used for the first time to design post-tensioned girders for bridge construction in Vietnam. Geopolymer Concrete (GPC) is a type of concrete that does not use conventional Portland cement binders. It is the product of the reaction between an alkaline solution and materials containing large amounts of silica and aluminum compounds. The use of GPC in bridge construction will have several practical implications for the bridge industry in particular and the Vietnamese construction industry in general, helping to reduce significant levels of CO_2 emissions and environmental pollution and promoting sustainable development. The post-tensioned I-girder in this study is designed using GPC that was created in the lab using materials available in Vietnam. With a fly ash content of 15% of the total volume, the compressive strength, tensile strength, and elastic modulus of GPC concrete samples at 28 days were 45.8MPa, 4.1MPa, and 35.5GPa, respectively. The design results have been compared with the standard to conclude about the bearing capacity of the beam.

Keywords: Geopolymer concrete, Prestressed girder, Bridge structure, Sustainable development

1. INTRODUCTION

In recent years, construction works in general and traffic works in particular have been built and increasingly developed to meet the requirements of industrialization and modernization of the country. The Asian Concrete Federation (ACF) estimates that each year, around 35 billion tons of concrete are produced globally, which means that about 4.2 billion tons of cement will be used [1]. According to Global Cement magazine data, Vietnam currently ranks fifth in the world in terms of cement production capacity, trailing only China, India, the United States, and Russia. Vietnam's cement production capacity has roughly tripled in the ten years since 2009, from 45 million tons to 120 million tons [2]. The cement manufacturing industry, on the other hand, is thought to cause severe pollution due to high levels of CO_2 emissions and dust, as well as high energy and natural resource consumption. One ton of cement produces approximately 1-1.2 tons of CO_2, and the cement industry contributes 5-7% of global CO_2 emissions as well as a significant amount of smog, which is now even higher [3].

In the current modernization, the demand for electricity consumption has increased significantly, which led to the development of thermal power plants. Fly ash is one of the waste products of these plants. The majority of fly ash is not used efficiently and is disposed of in landfills. In Vietnam, the utilization rate is not high, and it takes hundreds of hectares to store fly ash which greatly affects the environment. In order to gradually limit the use of Portland cement and take advantage of thermal power fly ash industrial waste, a new binder is being researched and gradually applied in construction practice. This binder incorporates thermoelectric fly ash as well as a number of common chemical compounds. This binder is known as geopolymer. The use of GPC for construction projects in general, and bridge projects in particular, will have a significant impact on reducing CO_2 emissions from cement production, contributing to sustainable development. Furthermore, because of its low dry shrinkage and good resistance to sulphate and acid corrosion, GPC can be used in constructions in coastal infrastructure areas that are heavily impacted by saline environments.

In addition to the benefits mentioned above, there are some drawbacks to using GPC. The first disadvantage is associated with the manufacturing process; specifically, changing the geopolymer binder content during the design process has a significant impact on GPC properties such as slump, setting speed, and strength. Therefore, it will be difficult to achieve design goals. During construction, the alkaline environment can also have an impact on the health of workers.

In the United States, the main application of geopolymer adhesives is the production of rapid-curing geopolymer cement, which has been used in military airports since 1985, as well as runways, industrial floors, and highways. In Australia, GPC has been used to produce prefabricated sleepers, sewer pipes, and precast concrete structures with the requirement of providing high strength at an early age after steam or heat curing. Brisbane West Wellcamp Airport is Australia's first GPC-built airport, with a capacity of approximately 70,000 tons of GPC [4] (Fig.1). Heavy-duty GPC was used for the turning node, apron, and taxiway pavements using a slip form paving machine. The proprietary GPC was found to be well suited for this construction method due to its high flexural tensile strength, low shrinkage, and workability characteristics. GPC use in the construction of this airport has reduced carbon emissions by 6,600 tons. This airport has become the greenest airport in the world.

Fig.1 Brisbane West Wellcamp Airport

Another advantage of GPC related to mechanical properties compared to Portland cement concrete (OPC): the ductility, the bond-strength and compression strength of GPC are higher than OPC [5, 6].

In the bridge construction industry, there are specific applications of GPC put into practice. Studies [7-9] have applied GPC for retaining walls at the bridgehead to withstand earth pressure loads. GPC is also being researched and used to design bridge beams [10]. These studies have demonstrated the viability of using GPC for bridge construction.

Fig.2 . Application of GPC for retaining wall [7]

In Vietnam, GPC has recently begun to be studied. These studies are primarily focused on determining the grade, GPC fabrication materials [11-12], studying the cracking behavior of GPC beams [13], and adhesion between GPC and reinforcement [14]. GPC has also been studied for use in porous concrete [15-16]

This study will present the research contents of GPC application for prestressed beams of bridge works based on domestic and foreign studies on GPC concrete. The use of GPC for bridge construction will have many practical implications for the Vietnamese bridge construction industry, such as avoiding the phenomenon of thermal cracking of large concrete blocks during hydration and protecting the environment in the pursuit of sustainable development. Furthermore, this is an excellent product for use in coastal infrastructure areas where the saline environment has a significant impact.

2. RESEARCH SIGNIFICANCE

In this study, GPC was first studied, fabricated, and used to design prestressed beams for bridge construction in Vietnam. The success of the research will bring many practical meanings in terms of science and practice. It is the basis for using GPC concrete for the construction industry in general and for the bridge industry in particular in Vietnam. It will significantly reduce CO_2 emissions and environmental pollution towards sustainable development. This issue is very important because Vietnam is a developing country, and the issue of environmental pollution is always a special concern of the government.

3. MATERIAL CHARACTERIZATION

3.1 Compositions of Geopolymer Concrete

Materials used to make GPC include binder (Fly Ash), water, coarse aggregate, fine aggregate, and activated alkaline solution. In this study, the fly ash used is class F fly ash taken from the Pha Lai thermal power plant with a density of 2.45 g/cm^3. Fly ash has an average particle diameter of about 28.47 µm and an area weight of about 950 kg/m^3. The strength activation index is at a high level, meeting the quality criteria and conforming to the regulations of ASTM C618 [17].

The large aggregate used is crushed stone of grade D10, which is taken from Phu Ly quarry - Ha Nam, Vietnam. The experimental results show that the density of the two rocks is 2,710 kg/cm^3, and the compacted volume is 1560 kg/m^3, respectively. Fine aggregate is Song Lo yellow sand. Sand has a density of 2630 kg/m^3 and a modulus of magnitude Mk = 3.00. The superplasticizer is a GPS-1000 additive that conforms to class D of ASTM C494 [18].

The composition of GPC is calculated according to ACI211.1 [19] of conventional cement concrete, taking into account aggregate grade to ensure the ease of compaction according to ACI 325.10R [20]. The component design method calculates the binder as conventional concrete.

The method of calculating the composition of the aggregate mixture is the same as that of the conventional method. The ratio of composition in large aggregates, including D10 rock and yellow sand, is 0.54 and 0.23, respectively. The selected aggregate ratio is compared with the grade according to ACI 325.10R. The design results of the aggregate mixture show that the aggregate mixture is suitable for mixing in today's modern batching plants.

The total binder content used was 377.15 kg/m^3. Fly ash is used to replace cement. GPC components are designed on the principle of ensuring normal slump speed, and even in the case of reducing slump, beams can still be constructed normally. The designed target slump for this concrete mixture is 12±2 cm, and the slump speed is monitored over time. For road construction by conventional vibrating compaction technology, the above-mentioned slump is suitable. The fly ash combining with the activated alkaline solution in the composition of GPC plays a role of both a binder and a micro-aggregate.

3.2 Manufacturing and Mechanical Characterization

The mechanical and physical properties of GPC are determined in the study using a standard cylinder sample of 150x300 mm at 7 days and 28 days of age, including the compressive strength of concrete determined according to TCVN 3118-1993. [21]; Tensile strength when split determined according to TCVN 3119-1993 [22], elastic modulus determined according to ASTM C496 [23]. Composition of GPC concrete mixes with a target strength of 45 MPa. GPC mixing was performed using a laboratory vertical cage mixer (Fig.3).

Fig.3 Mixing GPC

The process of sampling and testing to determine the compressive and tensile strength of GPC are shown from Fig.4 to Fig.6. These experiments were performed by the research team at 7 days and 28 days.

Fig.4 Molds after pouring GPC mixtures

Fig.5 An experiment to determine the compressive strength of GPC concrete

Fig.6 An experiment of tensile GPC concrete

Test results to determine the compressive strength of GPC concrete at 7 days and 28 days are shown in Table 1. The calculated values are averaged of 3 samples: M1, M2, and M3. The average compressive strength value obtained at 7 days is 35.7 MPa and increased rapidly at 28 days to 45.8 MPa. The average tensile strength of GPC at 7 days was 3.5 Mpa, and at 28 days was 4.12 MPa (Table 2).

Table 1. Results of compressive strength of GPC at 7 days and 28 days

Sample	Age (day)	Compressive strength (MPa)	Average Comp. Strength (MPa)	Standard deviation
M1		34.60		
M2	7	36.50	35.67	0.97
M3		35.90		
M4		46		
M5	28	45.30	45.83	0.47
M6		46.20		

Table 2. Results of tensile strength of GPC at 7 days and 28 days

Sample	Age (day)	Compressive strength (MPa)	Average Comp. Strength (MPa)	Standard deviation
M1		3.47		
M2	7	3.68	3.50	0.17
M3		3.35		
M4		4.03		
M5	28	4.25	4.12	0.12
M6		4.07		

The average elastic modulus determined from the combination of samples tested at 7 days and 28 days is 32.4 GPa and 35.5 GPa, respectively (Table 3). These elastic modulus values are quite high compared to conventional concrete.

Table 3. Results of the elastic modulus of GPC at 7 days and 28 days

Sample	Age (day)	Compressive strength (MPa)	Average Comp. Strength (MPa)	Standard deviation
M1		32		
M2	7	33	32.37	0.55
M3		32.10		
M4		35.60		
M5	28	34.80	35.50	0.66
M6		36.10		

4. APPLICATION OF GPC TO DESIGN POST-TENSIONED I-BEAMS

This study will use experimentally determined mechanical and physical properties of GPC concrete to design post-tensioned I-beams with a typical length of 33m. The bridge input parameters are assumed to be consistent with actual bridge construction in Vietnam.

4.1 Input Parameters

GPC concrete was used in the post-tensioned I-beam design. TCVN 11823-10:2017 [24] was used as the design standard, and the design live load is HL-93. The bridge was designed using seven I-beams with a span length of 32.2 m and a total width of 17.5 m to support four traffic lanes. The basic parameters of the designed bridge are summarized in Table 4.

Table 4. Basic parameters of the designed bridge

No.	Parameters	Value	Unit
1	Beam length	33	m
2	Span length	32.2	m
3	Bridge width	17.5	m
4	Barrier width	0.5	m
5	Roadway width	16.5	m
6	Number of beams	7	beam
7	Beam spacing	2.45	m
8	Number of lanes	4	lane

GPC concrete was only applied for prestressed beams, whereas ordinary reinforced concrete was used for the deck slab. The prestressed cable used in the design was seven-wire Low Relaxation strands with a tensile strength of 1860MPa and 12.7mm diameter, according to ASTM A416-96a [25]. Input parameters of design materials include GPC, conventional reinforced concrete, and prestressed cables, as shown in Table 5.

Table 5. Design material parameters

Materials	Parameters	Unit	Value
GPC concrete for beams	Specified compressive strength of concrete (28 days)	MPa	45.83
	Compressive strength of concrete at the time of initial loading	MPa	41.25
	Tensile strength when bending	MPa	4.26
	Specific weight	kN/m^3	24.5
	Elastic modulus	GPa	35.5
Conventional Concrete for deck slabs	Specified compressive strength of concrete (28 days)	MPa	30
	Tensile strength when bending	MPa	3.45
	Elastic modulus	GPa	28.11

Materials	Parameters	Unit	Value
Prestressed cables	Nominal diameter of 1 strand	mm	12.7
	Nominal area of 1 strand	mm^2	98.7
	Tensile strength	MPa	1860
	Yield strength	MPa	1674
	Elastic modulus	GPa	197

Fig.7 depicts a typical cross-section at the midspan of I-beams used in the designed bridge. The basic dimensions of the girder at the end and mid-span sections are shown in Table 6.

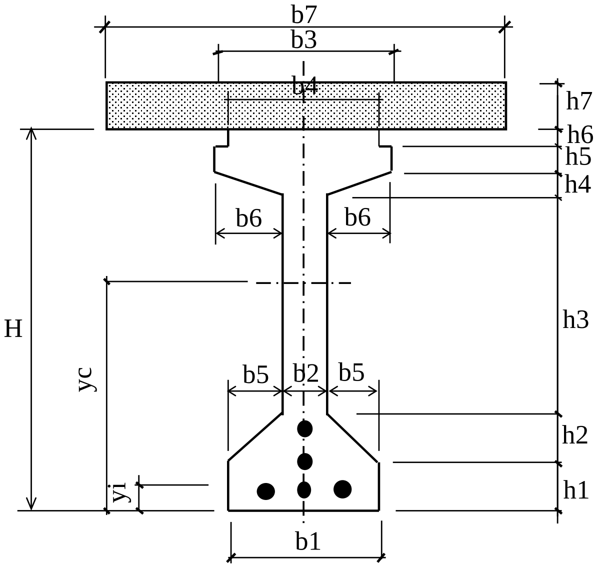

Fig.7 A cross-section at the midspan of beams

Table 6. Basic dimensions of girder at the end and midspan cross-sections

Symbol	Dimensions	End section (m)	Midspan section (m)
	Width		
b1	Width of the bottom flange	0.65	0.65
b2	Thickness of web	0.65	0.20
b3	Width of the top flange	0.85	0.85
b4	Width of haunch	0.65	0.65
b5	Width of bottom flange fillet	0.00	0.225
b6	Width of top flange fillet	0.10	0.325
b7	Effective width of deck slab	2.45	2.45
	Height		
h1	Height of bottom flange	0.25	0.25
h2	Height of bottom flange fillet	0.00	0.20
h3	Height of web	1.166	0.89
h4	Height of top flange fillet	0.034	0.11
h5	Height of top flange	0.12	0.12
h6	Height of haunch	0.08	0.08
h7	Thickness of the deck slab	0.20	0.20
H	Height of I beam	1.65	1.65
	Prestressed cables		
y1	1st tendon	1.34	0.45
y2	2nd tendon	1.065	0.26
y3	3rd tendon	0.79	0.11
y4	4th tendon	0.515	0.11
y5	5th tendon	0.24	0.11

Each I-beam applied 5 prestressed tendons, which consist of twelve 12.7mm strands. Fig.8 depicts the beam cross-sections and locations of tendons at the end and midspan sections. The vertical coordinates of the prestressed tendons are shown in Table 6.

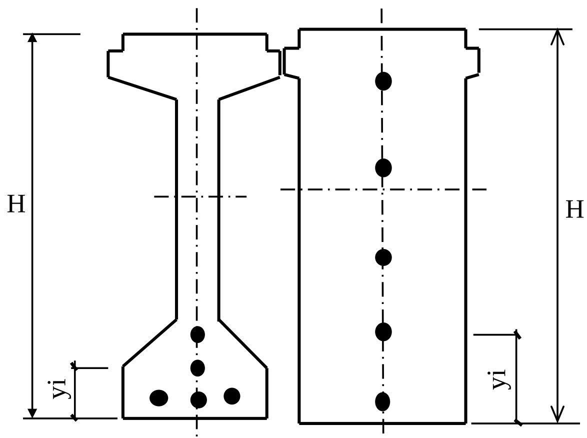

Fig.8 Locations of tendons at the end and midspan sections

4.2 Beam Test According to Limit States

The three basic stages of performance for a precast I-beam addressed in design are: (a) At transfer (noncomposite section S1); (b) At deck pour (noncomposite section S2); and (c) At service under dead and live loads (composite section S3).

Stage #1: The transfer stage refers to the time when the prestressing force in the strands is transferred to the precast I-beam at the plant, typically by cutting or detensioning the strands after a minimum concrete strength has been verified. Because only the beam self-weight acts at this stage, the most critical stresses are frequently at the beam ends, midspan, or harping points. Both tensile and compressive stresses are checked.

Stage #2: The stage at which the diaphragm and slab self-weight act on the non-composite I-beam. Note that the non-composite I-beam of stage #2 already become a prestressed beam, and thus it is different from the non-composite beam of stage #1.

Stage #3: At this stage, the bridge slab bonds with the I-beam to form a composite girder. The additional dead loads (e.g., barrier and wearing surface) in conjunction with the live load act on the composite girder. The AASHTO LRFD Service I and III load combinations are used to test this stage. Flexural strength is supplied to meet all factored loads. The different concrete flexural stress distributions at transfer, deck pour, and full-service loading are depicted in Fig.9.

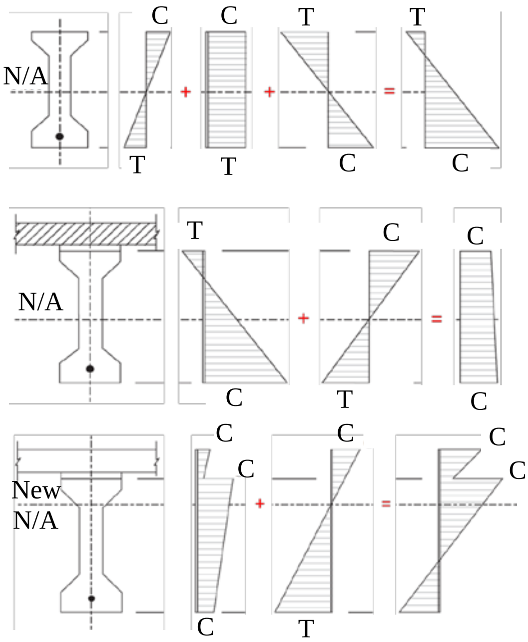

Fig.9 Three basic stages of performance for a precast I-beam

A comparison chart between factored moments M_u and flexural resistances M_r of the designed GPC beams at Strength I Limit State is shown in Fig.10. The result shows that the designed GPC beam satisfies the moment check at the Strength I Limit State.

Similarly, the designed GPC beam also satisfies the shear check according to the Strength I Limit State, as shown in Fig.11.

At Service I Limit State, the study conducted a content test of stress in beams during construction and operation. The stresses at the bottom fiber, the top fiber of the I-beam, and the top fiber of the slab are calculated for 3 performance stages (Fig.9). These stress values are compared with the allowable tensile and compressive stresses of the beam calculated according to Table 8, Article 9.4.2.1, Part 5 of TCVN 11823-10:2017.

The check of stresses at Service I and III Limit State for different performance stages of the designed GPC beam are shown from Fig.12 to Fig.14. The calculated results show that the stresses on the top and bottom fibers of the I-beam are all smaller than the stress limits for all the performance stages. That means the design I-beams ensure the bearing capacity during the construction and the exploitation.

5. CONCLUSIONS

The study introduced the process of making GPC concrete and then used this GPC concrete to design and fabricate a post-tensioned I-beam with a typical length of 33m. The use of fly ash accounts for 15% of the total volume of GPC. As a result, the compressive strength of 28 days old GPC was 45.8 MPa, the tensile strength was 4.12 MPa, and the elastic modulus was 35.5 GPa. The load test results of post-tensioned I-beams made of GPC concrete at the Strength and Service Limit States demonstrated that all test values met the design requirements. It shows that using GPC concrete for post-tensioned beams in bridge construction is both feasible and technical.

The research on manufacturing GPC concrete and the application of prestressed I-beam design in this study is a new step as a premise for the use of GPC concrete for bridge construction, reducing environmental pollution and moving towards sustainable development in the construction industry.

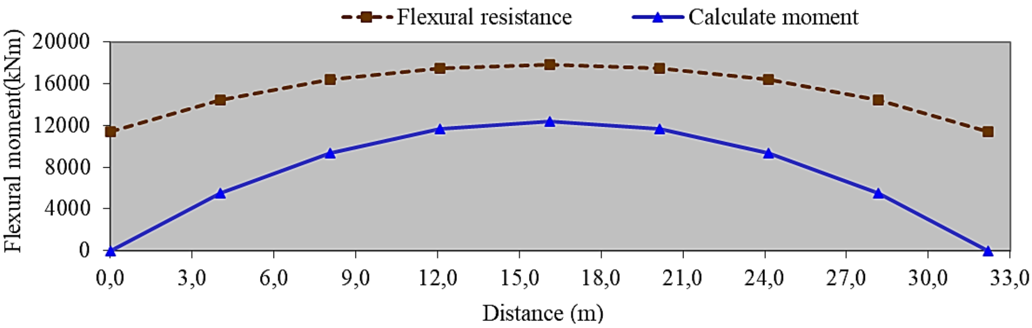

Fig.10 Moment envelops of the designed GPC beam.

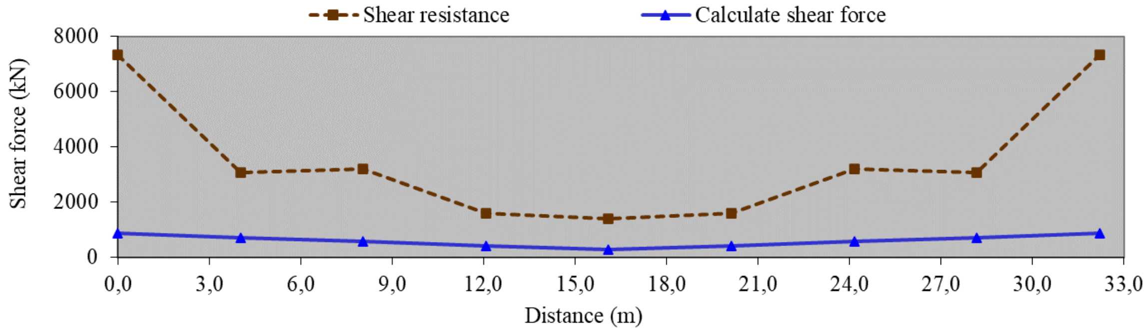

Fig.11 Shear envelops of the designed GPC beam.

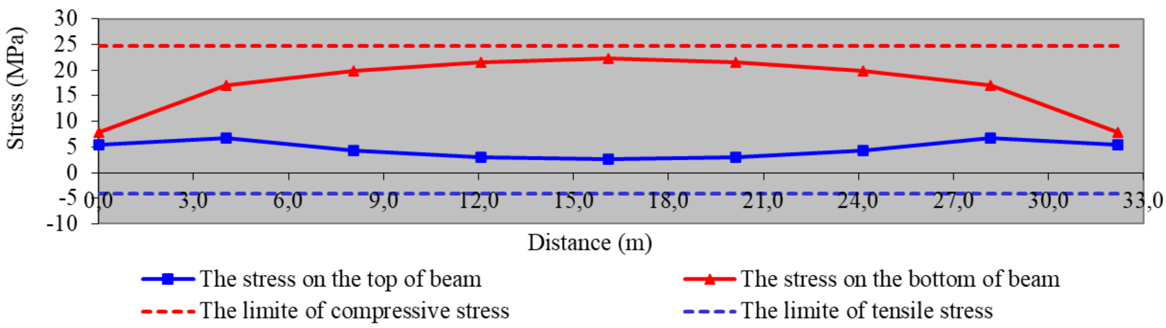

Fig.12 Stress test at stage 1 - the I - usage limit state

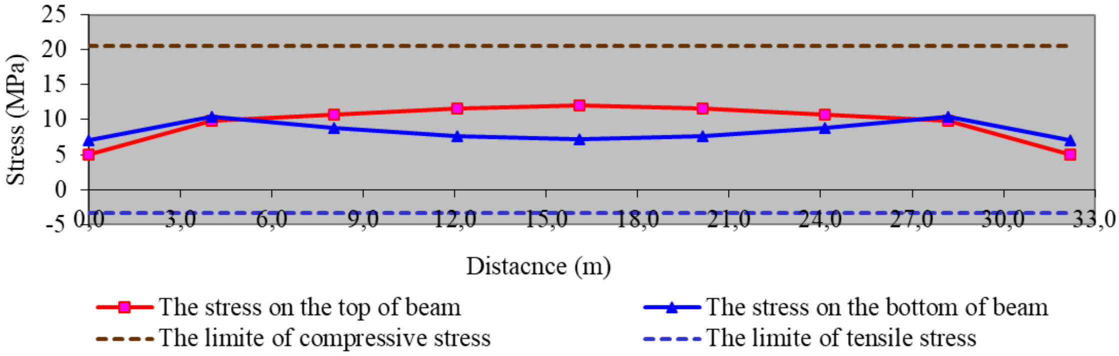

Fig.13 Stress test at stage 2 - the I - usage limit state

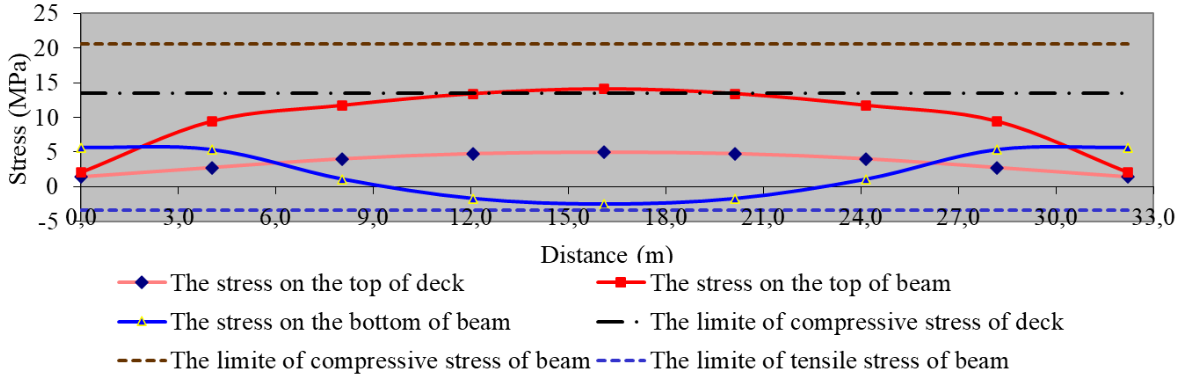

Fig.14 Stress test at stage 3 - the III - usage limit state

6. ACKNOWLEDGMENTS

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