

Testing of Load-Bearing Bridgework Structures Made of Arched Steel-Tube Confined-Concrete Elements with Carbon Plastic Casings

S N Valiev, A I Vasiliev, E S Mikhaldykin, V S Smolenkin

Moscow Automobile and Road Construction State Technical University (MADI)
Leningradsky Prospekt, 64 Moscow Russia 125319

E-mail: Mosti.madi@mail.ru

Abstract. The present paper presents the results of testing of steel-tube confined-concrete structural elements with polymer composite casings under various loading patterns. The tests were carried out for structural elements of different static patterns under static and low-cycle loads. Test samples were produced during proving the technology of manufacturing of such casings, so they have a certain number of defects. According to the tests, the reliability and durability of steel-tube confined-concrete structural elements were evaluated. Test results of samples with different braiding angles were compared, and the selection of the braiding angle of the pre-form for the second batch of tests was substantiated. A conclusion was made on the possibility of using such structures in transport construction as main load-bearing elements of transport structures; in particular, in construction of small road bridges.

1. Introduction

Search for net materials and structural solutions — both for conventional applications and for achieving previously-unattainable goals — is a high-significance area of contemporary engineering. The development and implementation of polymer composites (PCs) is among the key areas. In the Russian Federation there is a strong emphasis laid on production and implementation of PCs, as this area is in the list of industry development priorities (along with rare and rare-earth metals) [1]. In order to enhance polymer composites production, the development and implementation of innovative products are heavily sponsored [2].

In the field of construction (particularly, in bridge construction), the use of polymer composites jointly with traditional materials is one of the main and most promising areas. These structural solutions are being widely applied in various construction activities.

Steel-tube confined-concrete structures represent one of the ways to use polymer composites combining with concrete. The stress-strain state created in concreted by a PC casing (so called cartridge-clip effect) leads to enhancement of the concrete core's bearing ability (breaking load increases at the same cross-section area). Steel-tube confined-concrete structures with metal casings were studied at the end of the 19th century. It was professor A.A. Gvozdev who published the first monograph dedicated to the calculation of such structures; the paper was introduced in 1932.

Traditionally, steel-tube confined-concrete structures are considered mainly as compressible ones, where their potential is used to the greatest extent. The same is the case for steel-tube confined-



concrete structures with polymer casings. However, these structures are also studied under bending loads and off-center compression. Even bridge structures with such load-bearing elements were built — for instance, Kings Stormwater Channel Bridge (CA, USA) or Neal Bridge in Pittsfield (ME, USA). It should be noted that such studies of concrete-PC combination in steel-tube confined-concrete structures are mostly carried out abroad [3-12], while there are too few papers devoted to this topic published in Russia [13-20].

All bridges constructed in the world so far, which use steel-tube confined-concrete with PC casing as load-bearing structures, belong to the small bridges group. It makes sense to prove new technology at small bridges, especially because the small bridge problem is one of the acutest in Russian transportation system. As Federal Road Agency reports, small bridges constitute 80% of all engineering structures; of these, only 20% are in good state (according to the Ministry of Transportation data), 18% and 1% are considered to be in poor and critical state respectively. Along with the fact that lots of wooden bridges are in roadway operation now (66% of all bridges in the Arkhangelsk Region are wooden), it could be supposed that at least a half of the existing small bridges are to require renovation or replacement in upcoming decades.

2. Main Body

Within the R&D activities on the development of quickly-erectable structures, NIIGRIT JSC (against an order by VIAM FSUE) has studied the operation of steel-tube confined-concrete structural elements of various static patterns under static and dynamic (low-cycle) loading. Two batches of samples were tested in May and December 2015. For both batches, the following samples were tested:

- 4-meter long beams; four-point bend;
- 2-hinged arches with 8-meter spans; load applied in span center.

The tests were carried out using the testing equipment of Moscow State University of Civil Engineering on the CFM Schiller power frame. The loading was applied through vertical deformation (1 mm step) based on the readings of the hydraulic cylinder rod. Loading speed was 0.3 mm/s for beam samples and 0.2 mm/s for arched samples.

The testing casings were made by VIAM FSUE specialists. Test samples were produced during proving the technology of manufacturing of such casings, so they have a certain number of defects.

For first-batch tests in May 2015, steel-tube confined-concrete structures, reinforced with closed-contour braided sleeves, were made of carbon fiber with various acute angles (30° and 40°) directed along the structure axis. An angle less than 30° may deteriorate mechanical properties (strength and deformability) in radical direction, and also complicate concreting; also, it may lead to premature loss of the load-bearing capacity under loads.

Among the sample defects, there were longitudinal and transverse folds, production tooling marks, insufficient penetration zones, cross-section shape deformation, uncured samples, and local deviations of the reinforcement pattern.

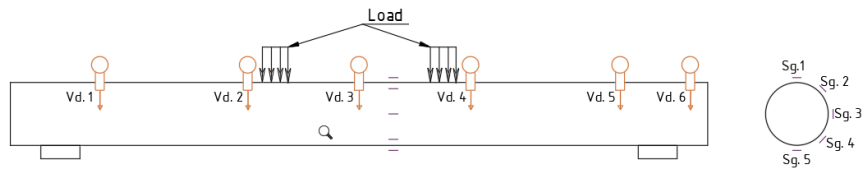
Sample parameters are given in Table 1.

Table 1. Sample Test Data

Casing	Carbon plastic VKU-51, 3 mm thick
Binder	Epoxyvinylether resin VSE-43
Reinforcement	Braided sleeve, carbon fiber Panex 35
Core	Concrete B 40, 300 mm in diameter
Effective Beam Span	3 m
Effective Arch Span	8 m

Figure 1 shows the test pattern for beam samples; Table 2 shows the test results.

Figures 2 and 3 show the test pattern for arch samples; Table 3 shows the test results.

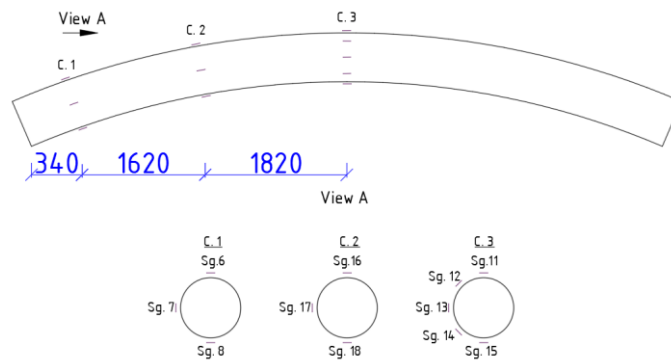


Sg is strain gage (resistance strain gage), Vd is vertical displacement indicator (deflection gage)

Figure 1. Beam Sample Test Pattern

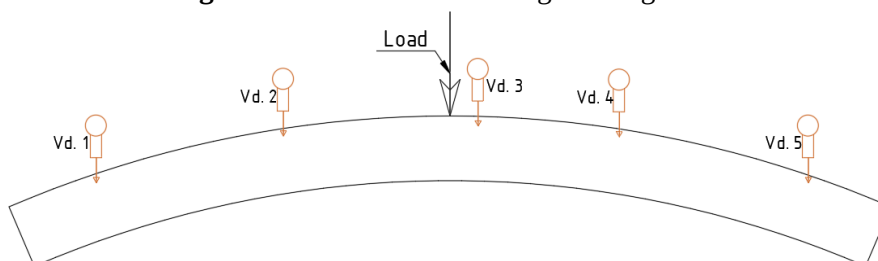
Table 2. First-Batch Beam Sample Test Results

	Braiding Angle (along the sample axis)	Breathing Load (on the hydraulic cylinder rod), ton	Displacement of the Hydraulic Cylinder Rod before Destruction, mm	Deflection Gage Readings before Destruction, mm		Cross-Section Rotation before Destruction, α°
				Vd 2	Vd 4	
B1	40	10.2	81.0	63.89	78.73	4.50
B2	30	10.3	45.0	29.82	37.82	1.98
B3	30	17.0	72.0	45.22	52.40	3.06
B4	40	9.9	108.0	74.45	66.20	5.17
B5	40	8.9	66.0	77.06	78.05	4.97
B6	40	6.9	96.0	77.47	74.47	4.79
B7	40	13.0	126.0	-	-	-
B8	40	14.0	72.0	-	-	-



Sg is strain gage (resistance strain gage)

Figure 2. Resistance Strain Gage Arrangement



Vd is vertical displacement indicator (deflection gage)

Figure 3. Arch Sample Test Pattern

Table 3. First-Batch Arch Sample Test Results

	Braiding Angle (along the sample axis)	Breeding Load (on the hydraulic cylinder rod), ton	Displacement of the Hydraulic Cylinder Rod before Destruction,mm	Deflection before Destruction , mm (indicator 3)
A-1	40	12.0*	109	98
A-2-1*	40	12.0*	46.0*	37.0*
A-2-2	40	19.0	84.0	63.0
A-3	40	15.0	84.0	32.0
A-4**	40	13.0	-	-
A-5	30	15.0	72.0	23.0
A-6	30	27.0	110.0	37.0
A-7***	30	27.0	-	-

Notes:

* - test stopped due to horizontal displacement of the bearing caused by a thrust;

** - destruction occurred at application of cyclic load;

*** - sample was brought to destruction after 10,000 cycles of a sign-constant 6-ton amplitude (17-23 tons) variable load.

Destruction of sample casings was featured as follows:

1) destruction of samples B1 and B8 took place in concrete; no significant casing damage;

2) in samples B2-7, A1-3, A6-7, casing was broken in the tensile zone at the load application point. With that, in all beam samples, the undestroyed part of the casing prevented falling of the structure; except or B3. Destruction of all beam samples was two-phase: concrete destruction and instantaneous casing destruction (in samples where it took place).

3) Samples A4 and A5 had two destruction zones — span center and quarter (this is due to asymmetry of the samples themselves).

Result analysis led to the following conclusions:

1) As expected, casings having sharper braiding angle along the axis of samples showed better results.

2) Asymmetry of the arched structure results in uneven distribution of stresses and further load-bearing capacity decrease.

Defects significantly depress the load-bearing capacity of structures. Considerable-size longitudinal folds had the greatest impact on the load-bearing capacity. Some beam samples were destroyed by a break in the longitudinal fold in the tensile zone (along the tensile stress rather than across it).

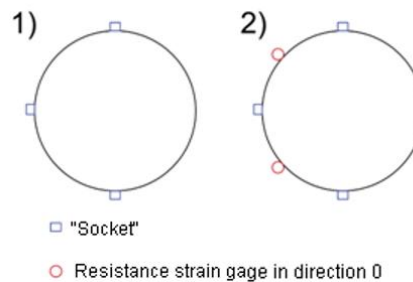
Samples B3, A6, and A7 had smoother shapes, higher symmetry, and fewer defects; they also had a sharper angle along the axis. Longitudinal folds were not pronounced or were even absent in the highest-tension zone. All that contributed to the greater load-bearing capacity. Besides, it should be noted that sample A7 was destroyed after a set of low-cycle tests. Preservation of the load-bearing capacity after these tests (same results of A6 and A7 tests) enables to estimate possibility of using such structures in bridgework construction, where loads are variable and usually have high amplitudes.

Samples with a braiding angle of 30° and double-thickness wall (6 mm) were made for repeating tests. Technology prove-out significantly decreased the number of defects. However, higher number of braiding layers lead to deep transverse (radial) folds that were not pronounced in the first batch. At the time of paper writing, VIAM FSUE specialists managed to remedy this defect, but all the second-batch samples had it. During production of the second batch, some new defects appeared; impact they had on the load-bearing capacity could barely be evaluated.

The test patter was similar to first-batch one, but with a set of adjustments; the key point was the increase of the number of resistance strain gages. This was because during first-batch tests, cross-

section deformation had a complicated nature, showing the loading-dependent height change in the tensile and compressed zone; also, the flat section hypothesis was not followed.

For beam samples, composite casing deformations were measured in three sections along the beam length (span center, span quarter, bearing zone). Each section had a socket of 4 resistance strain gages: (1) along the structure axis, (2) in radial axis, (3) along casing fibers. The sockets were located in three points around the section (top, bottom, and center). Auxiliary resistance strain gages were installed in the span center at the quarter-heights of the section (Figures 4, 5).



1) Near-bearing section and span-quarter section; 2) Span-center section

Figure 4. Arrangement of Resistance Strain Gages for Beam Samples

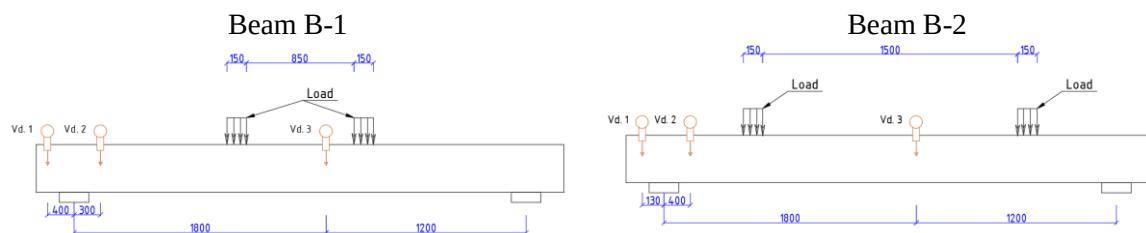
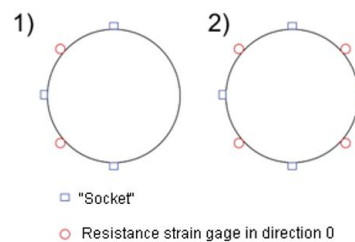


Figure 5. Beam Sample Test Pattern

For arched samples, resistance strain gages were arranged the same way as for beam samples, but with four sockets (Figure 6).



1) Near-bearing section and span-quarter section; 2) Span-center section

Figure 6. Arrangement of Resistance Strain Gages for Arched Samples

Table 4 shows the sample test results.

Table 4. Second-Batch Sample Test Results

	Load-Bearing Capacity, ton	Span-Center Bending, mm
Arch 1	24.5	19.5
Arch 2	32.5	38.6
Arch 3	30.4	50.0
Arch 4	31.2	52.3
Arch 5	27.1	42.5
Beam 1	18.0	14.0
Beam 2	45.0	63.0

The table above shows a significant spread of results. This could be explained by the complicated character of the impact of longitudinal folds, and the difficulty of evaluating new defects related to concreting of the second-batch samples. A reasoned regularity was found: the closer a longitudinal fold is located to the highest-stress section (span center, and span quarter and bearing zone to the lesser extent), the lower is the load-bearing capacity of a sample. The key scientific-value result of second-batch sample tests was the relative deformation measurement data. The readings of resistance strain gages are indicative of the complex character of the stress-strain state of the casing in such structures. Deformation patterns were similar for various samples, which proves the correctness of measurements and regularity.

In conclusion, durability of steel-tube confined-concrete elements with polymer composite casing. Durability characterizes their ability to bear with loads after a non-standard impact.

PCM-casing steel-tube confined-concrete elements belong to a low-angle zone (“pseudoplastic zone”) in the “load-displacement before destruction” diagram. In fact, while having a similar system behavior (deviation from linearity of displacements in the diagram during loading and residual deformation after load removal), this effect has another character of processes taking place. Residual deformation is mostly due to accumulation of system element faults. The major faults are:

- relaxation of stresses in casing structure defects appeared during manufacturing (folds etc.); at a specific value of stresses, folds are straightened — this is clearly seen in diagrams of resistance strain gage relative deformation (relative deformations decrease at the same load is due to relaxation of stress in defects — mostly fold straightening; curve jumps in diagram in Figure 7);
- appearance and accumulation of faults in the concrete core; initially it is expressed in the form of cracks in the tensile zone, and then concrete is destroyed in the compressed zone;
- accumulation of faults in the composite casing matrix — this causes redistribution of stresses between fibers and leads to higher involvement of the latter (deficient involvement of fibers at the initial stage is due to technological impossibility of the straight tensile state of all fibers during casing production);
- accumulation of fiber destructions; the law of fiber strength characteristics distribution for one batch is stochastic, which leads to gradual break of a part of the fibers as the load increases.

Figure 8 shows the tests results for the second batch of steel-tube confined-concrete structures with polymer composite casings. The diagram clearly shows the flat deformation zone starting at approximately 250-kN load (during testing of sample A-1, the hydraulic cylinder hinge was displaced, which damaged the sample and made further testing impossible).

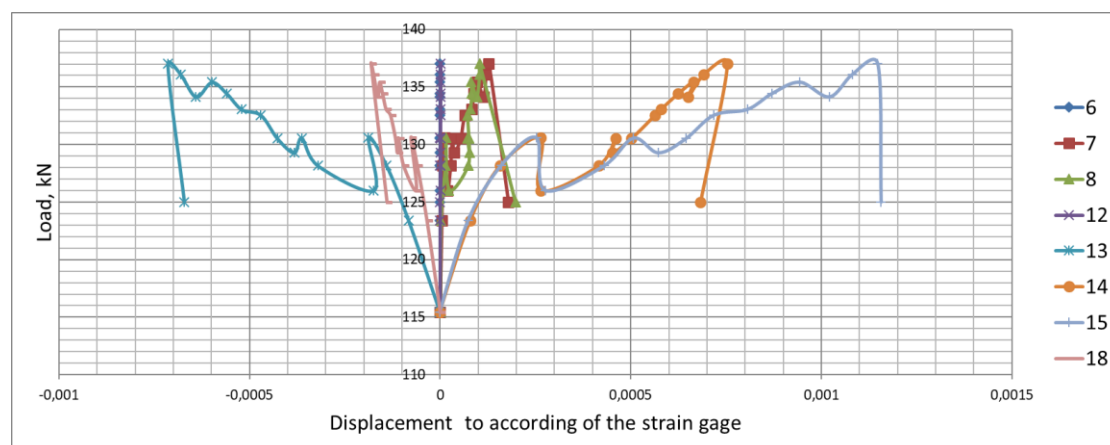


Figure 7. Resistance Strain Gage Readings (A-1, first batch)

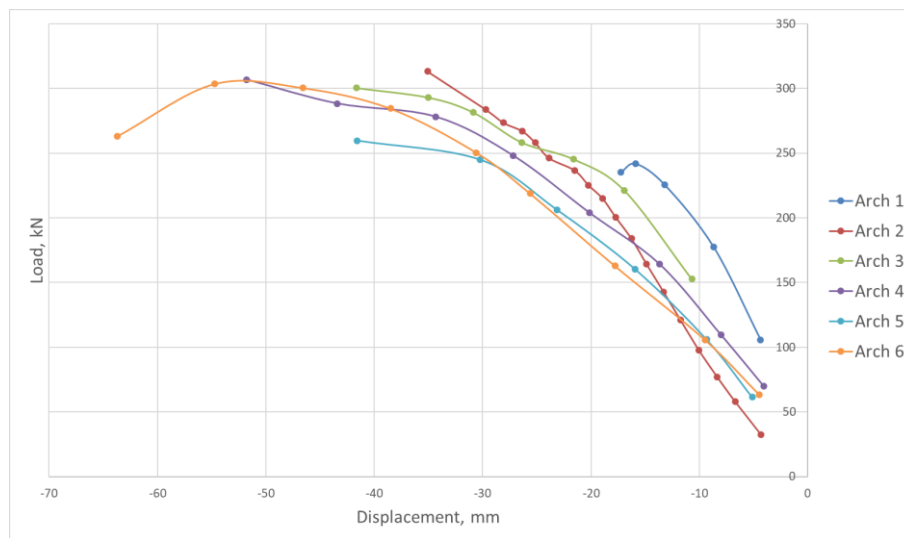


Figure 8. Second-Batch Arched Sample Test Results

Conclusion

The results of the studies carried out led to the following conclusions:

- reliability of steel-tube confined-concrete structures as load-bearing elements; despite the significant spread of the breaking load value, the area of the elastic work zone is similar for same-type samples, low-cycle tests showed no decrease in the load-bearing capacity;
 - durability of steel-tube confined-concrete structures with polymer casing was substantiated; this reduces the risk when constructing pilot facilities following the new technology;
 - data was collected to substantiate the simplified calculation method based on flat-section hypothesis;
 - dataset on the complex character of under-load casing deformation was collected. Processing the dataset is to bring an opportunity to find regularities of stress distribution in the casing and concrete core;
 - data on the degree of defect impact were collected, the most significant of them were identified.
- At the time of writing, process operations on preventing all existing defects that may affect the load-bearing capacity, had been developed.

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