ASSESSMENT OF THE EFFECTIVENESS OF COMPOSITE BANDS FOR RECONDITIONING OF DEFECTIVE SECTIONS OF PIPELINES

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The paper gives the results of testing 720 × 10 and 530 × 8 mm pipes with composite-polymer bands in sections with defects simulating local corrosion damage. Joint work of the band and pipe at static and cyclic loading caused by inner pressure is shown. Effectiveness of reinforcement of defective pipeline sections by composite-polymer bands is established and features of fracture of a banded pipe are noted.

Keywords: *pipeline, defective sections, strength restoration, composite polymer band, inner pressure, testing, stresses, deformation*

Problem of ensuring reliability of pipelines, which have been in service for a long time, requires availability of design solutions and technologies for their implementation aimed at increasing the reliability of individual damaged sections. This problem is particularly urgent for Ukraine, in the territory of which more than 42,000 km of just the main oil-, gas- and product pipelines are in operation.

Repair of pipeline sections with local corrosion-mechanical damage can be performed using design-technological solutions, realized either with application of welding, or with application of high-strength non-metallic materials [1]. Often here one of the conditions is performance of repair operations without interruption of pipeline operation. Under field conditions, far from power sources, application of bands from non-metallic materials is usually preferred for liquidation of local defects. Simplicity of the technology of band mounting with application of high-strength non-metallic materials and their small weight are the decisive advantages at selection of the technology of pipeline repair in mountainous regions on rocky soil.

In the world practice investigations in the field of application of composite materials at repair of oil- and gas pipelines have been performed during the last 20 years [2]. There are research programs funded by companies operating the pipelines and pipe manufacturers, the realization of which enabled including composite materials into pipeline repair technologies. A normative base was developed for pipeline repair by non-metallic composite systems under field conditions [3]. The range of the used composite materials is becoming wider [2].

In Ukraine local repair of pipelines is performed using composite bands PPS of «Polipromsintez» Company based on glass-fiber-plastic and polyester resin. A large scope of research was performed on calculated evaluation of the strength of pipeline — composite band system, studying mechanical properties of the composite band, development of design-technological schematics of reinforcement of pipeline defective sections. Unfortunately, application of composite materials based on glass-fiber-plastic and polyether resins does not have a well-established and stable technology. The wide range of composites and techniques, high sensitivity of mechanical properties to the change of technological parameters requires allowing for the technological features of materials and special features of repair operation performance when designing the composite bands [1].

In Russia composite polymer bands (CPB) are becoming applied for local repair of pipelines. The codes [3] specify defects in pipes repairable with CPB, materials recommended for defects filling and used as adhesives, materials taking the load applied by inner pressure, and fillers. Specifications for these materials and technologies of CPB application have been defined.

On the other hand, increased number of design-technological solutions on reinforcement of pipelines by CPB and widening the range of the used materials is not accompanied by an increase of the scope of investigations of joint work of the pipe and band. An essential difference in the moduli of elasticity, as well as mechanical and deformation properties of pipe and composite materials requires a more profound study of their joint work, particularly in the elasto-plastic and plastic deformation fields.

The purpose of this work was studying on full-scale pipe fragments and on samples the features of joint work of the pipe with a local defect and reinforcing

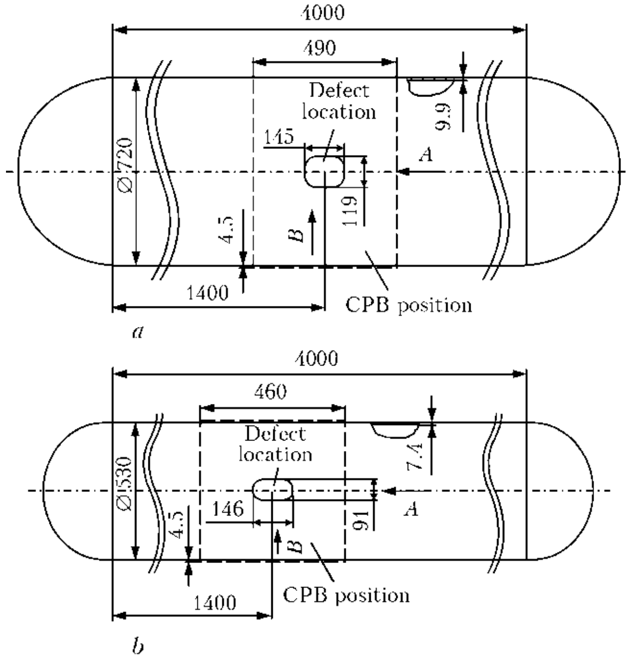

Figure 1. Samples-stands Dn 720 (*a*) and Dn 530 (*b*) with artificial defects and CPB

CPB, as well as assessment of the effectiveness of CPB application to increase pipeline strength under static and dynamic loading by inner pressure.

Investigations were performed on fragments of Dn 720 × 10 pipe made (TU 14-31573–96) from steel of 13G1S-U grade, and Dn 530 × 8 pipe made (TU 14-8-20–99) from steel of 17G1S-U grade. Semispherical caps were welded to 4 m pipes. Artificial defects were made on pipe outer surface with an abrasive wheel, the defect dimensions are given in Figures 1 and 2.

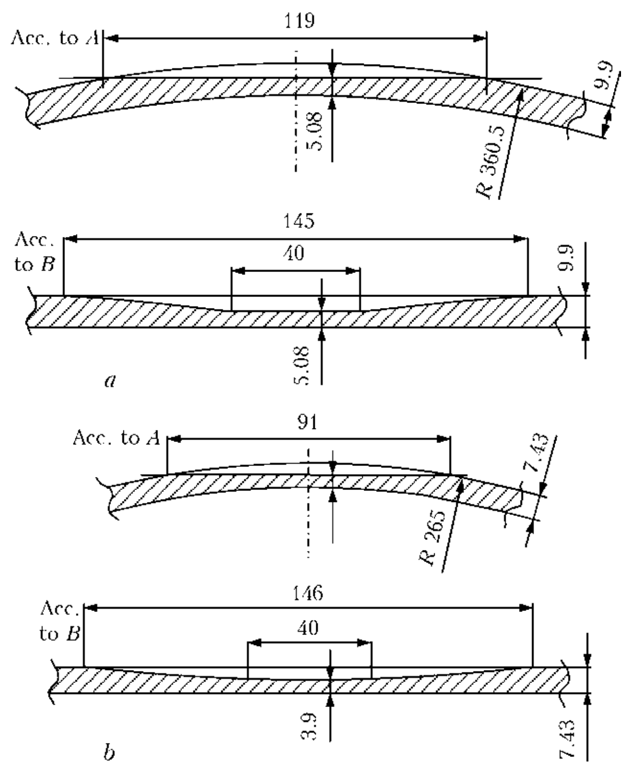

Figure 2. Geometrical dimensions of defects on samples-stands: *a* — Dn 720; *b* — Dn 530

Coefficients of lowering of the pipe load-carrying capacity were determined, proceeding from the prerequisite, that the defect influence is similar to that of an isolated through-thickness hole at equality of the areas of the defect and hole in the longitudinal direction [4–6]. Proceeding from the actual dimensions of defects, strength coefficients were equal to: for Dn 720 × 10 pipe — 0.72, for Dn 530 × 8 pipe — 0.617.

Defective sections were reinforced by applying a multilayer band. Technology of CPB application envisages preparation of the pipe surface by sand-blasting, as well as filling the defects and smoothing the roughnesses, in particular, in the presence of reinforcement in the weld, using REM-Steel composite material, the specification of which is given in TU 2257-005-00396558–98. After polymerization of REM-Steel and surface cleaning in keeping with VRD 39-1.10-013–2000 CPB was applied. For both pipes the band consisted of seven layers of glass net, and its thickness was equal to approximately 4 mm. Band width for Dn 720 pipe was equal to 490 mm, and for Dn 530 pipe it was 460 mm. All the operations on band mounting were performed at excess pressure of 4.94 MPa in pipes, that corresponds to 70 % of the working pressure. After complete polymerization of the band pipe testing began.

Testing program envisaged determination of the actual mechanical properties of metal of Dn 720 and 530 pipes; measurement of the actual wall thickness in the studied pipe fragments; investigation of the stress-strain state of samples-stands at the elastic stage of loading; testing of sample-stand Dn 530 at cyclic loading; testing of samples-stands by inner pressure to fracture; investigation of joint work of pipe wall with REM-Steel; and testing a shell with CPB for flattening.

Mechanical properties of pipe metal were determined on standard samples cut out of reference-shells cut off the pipe, and on samples made from the pipe after its failure. Testing results meet the specification requirements both for Dn 720 pipe and for Dn 530 pipe.

Measurement of wall thickness was conducted by ultrasonic thickness meter TUZ-2 in order to establish its actual value and scatter region on 4 m pipe. For sample-stand Dn 720 measurement results were in the range of 9.77–10 mm at the average value of wall thickness of 9.9 mm. For Dn 530 the range of wall thickness measurement was 7.36–7.53 mm at average value of 7.43 mm.

Stress-stain state of samples-stands was studied in order to determine the joint work of the pipe and band at all the loading stages, corresponding to pipeline operation. Relative deformations were measured using wire strain gauges of 5P1-20-200-B12 type with 20 mm base and static deformation measurer ISD-3. Deformations on the pipe wall and bands in defect locations and at a distance from them were measured in the longitudinal and circumferential directions. Figure 3 gives the transducer layout.

It should be noted that transducers were pasted to the pipe in the absence of inner pressure, and on the band — at the pressure equal to 70 % of working pressure. Deformations were measured at stage-by-stage pressure lowering to zero and subsequent increase of inner pressure to 9.81 MPa. Results of deformation measurement in the circumferential and longitudinal directions are given in Figure 4.

As is seen, zero deformations in the band correspond to 4.94 MPa pressure in the pipe. Zero deformations in the pipe are found in the absence of inner pressure. Compressive deformations are found in the band.

The given data indicate that band deformation occurs simultaneously with the pipe both at pressure lowering and at its increase. Deformation gradient in the defect zone (transducers 2 and 3) and in the zone of the longitudinal weld (transducer 1) is higher. This is less pronounced in sample-stand Dn 530. Circumferential and longitudinal deformations in the pipe body and on the band outside the zone of the defect and weld (transducers 5 and 7) are practically the same. At 9.81 MPa pressure a deviation of deformations from the linear law is found that is related to achievement of yield stresses in the pipe.

The band starts taking up part of the forces after the pressure rises above that at which it was applied.

An important element of checking the joint work of the pipe and band was testing for cyclic load of sample-stand Dn 530. Loading was performed by ex-

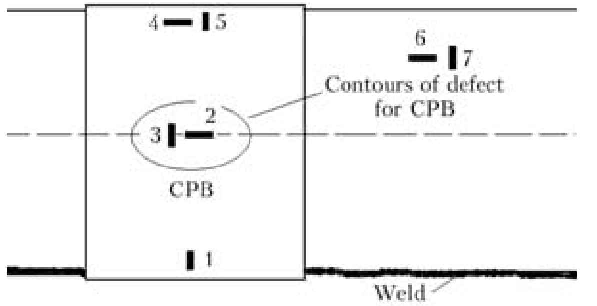

Figure 3. Layout of transducers (strain gauges) on samples-stands Dn 720 and Dn 530

cess hydraulic pressure of 0.4–7.5 MPa. The period of stress cycle was equal to about 36 s. Fatigue life of 10^4 cycles was taken as the test base that corresponds to 33 years of pipeline operation. Load was applied by PTR 1-1-400 hydraulic machine with 1000 l/h efficiency. Control of loading process was performed in the automatic mode. Loading parameters were controlled by highly accurate manometer and Metran 100-DI pressure sensor. Maximum cycle stresses were equal to about $0.6\sigma_y$, i.e. testing was performed in the elastic region. After 2500, 5000 and 8000 cycles, as well as after completion of testing (10,036 cycles) the pipe and band were examined. No delaminations or cracks in the band, or band delaminations from the pipe body were found.

Testing to fracture was performed on samples-stands Dn 720 and Dn 530. Dn 530 sample-stand was first subjected to cyclic testing. Load was increased in steps with 10 minute holding after each step and visual examination of the pipe and band. Loading steps envisaged: working pressure; 1.5 times working

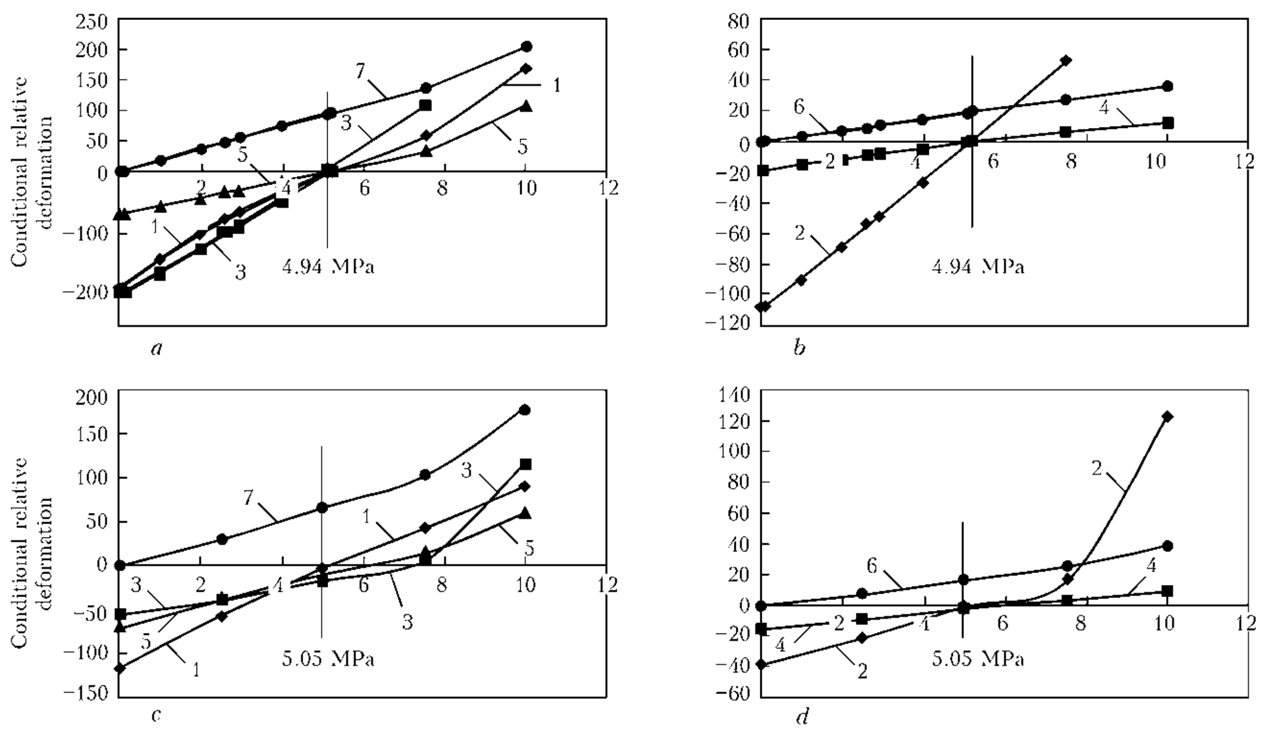

Figure 4. Results of measurement of circumferential (*a*, *c*) and axial (*b*, *d*) deformations of sample-stand Dn 720 (*a*, *b*) and Dn 530 (*c*, *d*): *1–7* — numbers of transducers of strain gauges

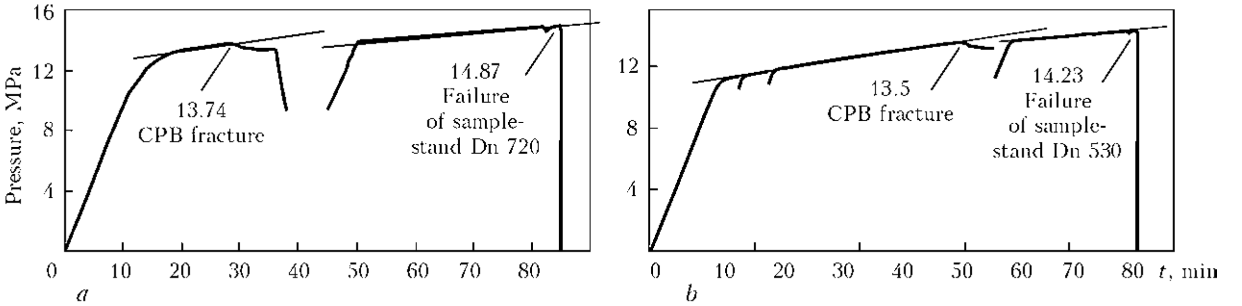

Figure 5. Diagrams of hydraulic testing of samples-stands Dn 720 (*a*) and Dn 530 (*b*) by inner pressure to fracture

pressure, pressure corresponding to material yield point; breaking pressure of sample-stand. Testing sequence required additional stops in the plastic region of pipe operation that is related to band fracture, which was observed before pipe failure. Complete diagrams of testing samples-stands are given in Figure 5.

Failure of a pipe reinforced by CPB has its special features. At loads inducing plastic deformation of the pipe, a field of deformation concentration starts forming in the defect location. When deformations have reached critical values for the band, its rupture occurs, which does not cover the entire width of the band, but just one part of it located above the defect. Here no delamination of the band from the pipe is observed. At the moment of band rupture the pressure in the pipe drops somewhat, and then starts rising again, and exceeds the level of initial band rupture. At this stage the angle of inclination of loading diagram decreases somewhat which is indicative of slowing down of load increment, and more intensive strain increase. Failure of sample-stand Dn 720 (Figure 6) is tough,

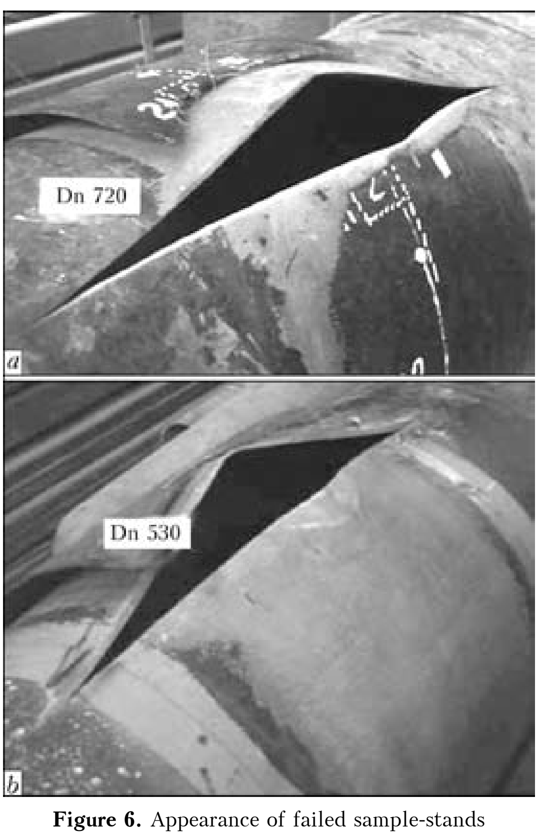

Figure 6. Appearance of failed sample-stands

and it occurred at inner pressure of 14.87 MPa. Here, a longitudinal crack formed, which ran through defect center. Immediately before pipe failure, band delamination occurred in the defect zone accompanied by characteristic crackling.

Testing of sample-stand Dn 530 was conducted by the same schematic as that of Dn 720. At the pressure of 13.5 MPa the first rupture of part of the band occurred (about 30 % of its width). Pipe failure occurred at the pressure of 142.3 MPa (Figure 6, *b*).

Generalization of the results of testing samples-stands Dn 720 and Dn 530 is given in the Table.

A criterion for assessment of CPB effectiveness can be comparison of strength coefficients of band-reinforced pipe, and coefficients of pipe wakening by the defect. Strength coefficient of a pipe reinforced by a band is considered proceeding from partial fracture of the band and complete failure of the pipe with the band.

Sample-stand Dn 530 demonstrated a slightly lower effectiveness of the band. It is possible that the result may have been affected by its preliminary testing by cyclic load, as well as application as initial mechanical properties of the results obtained on samples, cut out of the pipe after its testing to fracture. It is also possible that the band effectiveness is somewhat decreased with increase of pipe weakening by the defect.

As is seen, the effectiveness of band application is significant, even if partial rupture of the band is taken as the limiting state. On the other hand, it is clear that 100 % restoration of pipe strength requires such a considerable increase of band thickness which will be not cost-efficient.

Coefficients of pipe weakening, given in the last column of the Table, were derived proceeding from minimum values of ultimate strength of steels given in the pipe specification. This characteristic is quite conditional, as the specified values of pipe mechanical properties are below the actual value.

To get an idea of joint deformation of the metal of the pipe and REM-Steel tensile testing of samples with a layer of REM-Steel applied on them was conducted. Samples were cut out of a reference-shell Dn 720. Three samples were tested to varying degrees of plastic deformation.

Loading in the first sample was taken to its necking. Stresses here were equal to 568.8 MPa that prac-

Results of testing samples-stands Dn 720 and Dn 530 to failure

Pipe Dn	Minimum wall thickness (actual), mm	Strength properties of steel				Stresses in the pipe at band fracture, MPa	Pipe breaking stresses, MPa	Coefficient of weakening of defective pipe φ	Coefficients of weakening of pipe reinforced by a band	
		Acc. to TU (min), MPa		Test, MPa					Against actual properties	Against specification requirements
		σ_y	σ_t	σ_y	σ_t					
720 × 10	9.77	380	540	388.20	560.60	518.93	540.5	0.720	0.927/0.964	0.961/1
530 × 8	7.36	360	510	391.65*	560.65*	479.30	504.2	0.617	0.864/0.910	0.940/0.989

*Minimum mechanical properties obtained on samples cut out of the pipe after its testing.

tically corresponds to ultimate strength of steel. Relative elongation in the sample, measured after relieving of the load, was equal to 17 %. Cracking and delamination of REM-Steel was recorded at stresses of 505 MPa.

At testing of the second sample stresses reached 538.6 MPa, residual deformations were equal to 4.25 %. Start of delamination in this sample was recorded at the stress of approximately 505 MPa.

In the third sample, when stresses reached 468.8 MPa, loading was interrupted. Here, residual elongation was 1.5 %. No traces of delamination or cracking of REM-Steel were found in this sample.

This testing confirmed that at elastic and elasto-plastic deformations REM-Steel works together with the pipe metal. Delamination and cracking are found when plastic deformations are equal to 2–3 %.

If these results are transferred to the pipeline, one can see that delamination of REM-Steel occurs at the very final stage of pipe loading, when the site of deformation concentration is determined.

Joint work of the pipe and band at deformation was checked by testing the shell with the band for flattening. Testing was aimed at determination of the relative deformation, at which the joint work of the metal and the band is disturbed. Band rupture took place at flattening of Dn 530 shell with the band up to 220 mm distance between the outer walls. At load relieving this distance increased to 265 mm. Relative deformation of metal, at which band cracking occurred, was equal to about 7.8 %. This result is another confirmation of the joint work of the band and the pipe at quite high local plastic deformations.

On the other hand, tensile testing of samples in the form of bands 44 mm wide, cut out after fracture of sample-stand from the band section, removed from the fracture point, showed that the band material works in the elastic region right up to fracture. Relative elongation of samples is practically zero. However, at simultaneous work with the pipe, band fracture occurs, as was noted above, at sufficiently high plastic deformations in the pipe. This is attributed to the fact that the composite modulus of elasticity is more than two orders of magnitude lower than that of steel, the band is applied onto a loaded pipe and the band is capable of taking up plastic deformations of the pipe partly at the expense of the filler ductility.

CONCLUSIONS

1. Results of testing fragments of pipes reinforced by CPB in defective locations showed that deformations in the bands are proportional to pipe deformations. This is indicative of simultaneous work of the pipe and the band not only in the elastic region at tensile and compressive stresses in the band, but also in the region of elasto-plastic deformations in the pipe.

2. Pulsed cycle testing with maximum cycle stresses corresponding to working pressure in the pipe, showed the joint work of the pipe and band in the entire testing base (10^4 cycles) and did not induce any fatigue cracks.

3. At the given combination of geometrical dimensions and mechanical properties of the pipe, defect dimensions and conditions of placing the band, fracture of the latter precedes exhaustion of the pipe load-carrying capacity. Band rupture occurs in the defect location at the stage of concentration of plastic deformations in this zone is of a local nature and is not accompanied by delamination of the band from the pipe.

4. Results of testing samples-stands Dn 720 and Dn 530 showed that band fracture occurs at stresses which are equal to 86.4–92.7 % and pipe failure — at 91.0–96.4 % of values of tensile strength of pipe metal. This is indicative of the fact that the band significantly increases the strength of a defective pipe.

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