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INSPECTION AND PROPOSAL FOR THE REPAIR METHOD OF A CRACKED EXPANSION JOINT ON HEAT EXCHANGER USING COMPOSITE SLEEVES

KONTROLA I PREDLOG METODE REPARACIJE OŠTEĆENOG DILATACIONOG SPOJA IZMENJIVAČA TOPLOTE POMOĆU KOMPOZITNIH ČAURA

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Keywords
- inspection
- repairing method
- crack
- heat exchanger
- composite sleeve

Abstract

A heat exchanger is a heat transfer device that exchanges heat between two or more process fluids. Heat exchangers have widespread industrial and energy applications. The actual design of heat exchangers is a complicated problem. The cost of fabrication and installation, weight, and size play important roles in the selection of the final design from a total cost of the ownership point of view. In this work we present a modern technique to repair the structural defect of the steel extension joint. This technique uses a composite sleeve. By using the database obtained from the service location, we perform a numerical analysis to estimate the hoop stress distribution which is responsible for failure. According to the obtained results, the composite sleeve is considered as a suitable method for repairing the circumferential crack in the steel material. In fact, the superior fatigue performance of composite material sleeves enables them to be used to repair metallic materials with fatigue damage. Finally, this work confirms that the composite sleeve can be considered as a suitable technique to repair expansion joint cracks under high temperature.

Ključne reči
- kontrola
- metoda reparacije
- prslina
- izmenjivač toplote
- kompozitna čaura

Izvod

Izmenjivač toplote je uređaj za prenos toplote kojim se razmenjuje toplota između dva ili više procesnih fluida. Razmenjivači toplote imaju široku industrijsku i energetsku primenu. Stvarni dizajn izmenjivača toplote je kompleksan zadatak. Troškovi proizvodnje i ugradnje, težina i veličina igraju važnu ulogu u izboru konačnog dizajna sa stanovišta ukupnih troškova. U radu smo predstavili modernu metodu za reparaciju defekta u delu čelične konstrukcije dilatacionog spoja izmenjivača. Ova metoda je metoda kompozitne čaure. Koristeći bazu podataka dobijenu sa servisne lokacije, izvršili smo numeričku analizu radi procene raspodele obimskog napona, usled kojeg je nastalo oštećenje. Prema dobijenim rezultatima, kompozitna čaura se smatra pogodnom metodom za reparaciju obimske prsline čelične konstrukcije. Zapravo, superiorne osobine kompozitnih čaura s obzirom na zamor omogućavaju njihovu primenu u reparaciji metalnih konstrukcija sa oštećenjima usled zamora. Konačno, u radu se potvrđuje da se metoda kompozitne čaure može smatrati odgovarajućom tehnikom za reparaciju prslina dilatacionih spojeva pri visokim temperaturama.

INTRODUCTION

A heat exchanger is a heat transfer device that exchanges heat between two or more process fluids. Heat exchangers have widespread industrial and energy applications. The actual design of heat exchangers is a complicated problem. It involves more than heat-transfer analysis alone. The cost of fabrication and installation, weight, and size play important roles in the selection of the final design from a total cost of ownership point of view.

Differential longitudinal expansion between the shell and the tube bundle is a well-known problem in fixed tube sheet heat exchanger design. Differential expansion occurs from two sources: a) temperature; and b) pressure. The expansion changes with temperature. In the current case, the expansion value at 250 °C is equal to 5 mm as indicated in Table 3.

In many cases, heat exchangers face serious problems such as corrosion, erosion, fatigue, and other. These problems may create single or multiple cracks. The main factor which is responsible for these problems is high temperature or change of temperature. In order to maintain the heat exchanger under service, it should be always under surveillance and control. In addition, material defects are repaired by different methods such as, welding, metallic contact, composite sleeve, or patching. In particular, composite materials are used in industrial companies to repair materials due to their excellent properties, such as the ability to return mechanical properties of the defected material and increase its lifetime.

The repair of pipelines and heat exchangers using composite materials has been widely accepted. The primary drivers behind the acceptance of this repair method have been composite manufacturers who have developed the repair systems and operators who have benefitted from their capabilities. The advantages in using composite materials for repairing damaged systems over conventional welded steel repairs include ease of installation, no welding, safety, ability to leave systems in service, and economics. Accompanying the acceptance of composite materials have been extensive research efforts, primarily funded by the pipeline industry. Groups such as the Pipeline Research Council International, Inc., Gas Research Institute, oil and gas pipeline companies, and composite manufacturers have funded these programmes. Research has been aimed at evaluating a wide range of anomalies including corrosion, dents, mechanical damage, defective seam and girth welds, and wrinkled bends. In these programmes, more than 20 different systems have been evaluated. As a result, the industry's knowledge has advanced significantly. Alexander et al. /1/ proved that the efficiency of composite material at elevated temperatures is considered an optimal method for repairing pipelines. They also present the most important features of the Composite Standards which is the organisation and listing of ASTM tests required for material qualification of composites (i.e., matrix and fibres), filler materials and adhesives. Listed below are several of the ASTM tests given in ASME PCC-2, /1/:

- Tensile strength: ASTM D 3039
- Hardness (Barcol/Shore): ASTM D 2583
- Coefficient of thermal expansion: ASTM E 831
- Glass transition temperature: ASTM D 831, ASTM E 1640, ASTM E 6604
- Adhesion strength: ASTM D 3165
- Long term strength (optional): ASTM D 2922
- Cathodic disbondment: ASTM G 8

The objective of this work is to investigate the ability of the composite sleeve material as an appropriate technique for repairing the expansion joint defect under high temperature using different sleeves compared with a metallic contact method. This report was conducted to improve the durability and performance of heat exchanger expansion joints.

Problem description

A circumferential crack has occurred in the expansion joint of the heat exchanger during service operation, as shown in Fig. 1. The current exchanger was subjected to a service pressure and different temperatures during the whole day. It is well known that there is significant influence between high temperature and growth crack in steels, including shock cooling.

It is reminded that European standards NF EN1504-9 and NF EN1504-10 define principles to be followed and provide methods for repair or reinforcement that allow for compliance with the principles, as indicated in the summarised Table 1, extracted from the standard NF P95-103. The table provides information on various treatments for cracks.

Figure 1. Location of circumferential crack in the expansion joint of heat exchanger.

Table 1. Partial extract from Table #1 of NF EN1504-9 related to crack treatment methods (taken from standard NF P95-103).

Principle	Reference methods and standards	Comments
Principle 1 -	1.4 Superficial sealing of fissures (fissure bridging) 1.5 Fissure sealing (NF EN1504-5) 1.6 Transformation of fissures into joints	In addition to these methods, it is appropriate to include caulking, which is not explicitly addressed by the standards of the NF EN1504 series.
Principle 4 - Structural reinforcement	Injection into cracks, voids, or interstices (according to NF EN 1504-5).	A mere injection of cracks is generally insufficient to ensure complete structural reinforcement. Additional reinforcement methods are often necessary (refer to repair or strengthening methods 4.1 to 4.4 and 4.7). Pre-sealing of the cracks is generally required.
	For reference: 4.6 Sealing of cracks, voids, and interstices (NF EN1504-5)	The plugging, not aiming to completely fill the crack, is not considered by the NF P95-103 standard as conforming to the principle of structural reinforcement.

Various characteristics of a crack (width, opening, path, depth, activity (passive or dormant, active), breath or movement, etc.) are defined by the NF P95-103 standard, which complements, as necessary, the standards in the NF EN1504 series. Different crack treatments are synthesized in Fig. 2, adapted from Fig. 2 of NF P95-103 standard, and are defined below.

The following figure shows that a number of technical terms have not been translated consistently in the NF EN 1504-9 and NF EN1504-10 standards. Furthermore, repair methods have been added in the NF EN1504-9 standard. This complicates the reading of these texts. Therefore, it was necessary to redefine all the terms in the drafting of the NF P95-103 standard in order to avoid confusion and also to add the treatment by sealing, which is not covered by the standards in the NF EN1504 series.

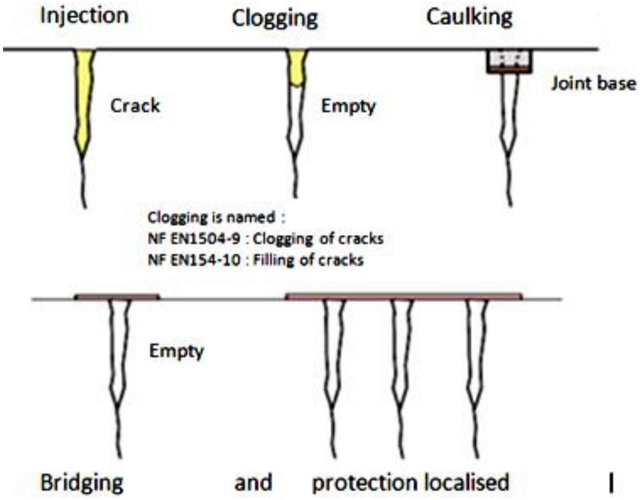


Figure 2. Different crack treatments.

The choices of products or systems related to a crack injection operation concern, on one hand, the injection product itself and, on the other hand, the crack sealing product, which is essential to seal the crack lips during injection in order to maintain the injected liquid until its setting. In our current case, in its generality:

- recalls the repair methods in accordance with principles 1 and 4,
- summarizes the key points of the standard NF EN1504-5 that must be known in order to use it,
- then lists various selection criteria:
  - injection specificity,
  - families of usable products and systems,
  - certification marks,
  - health and safety, and environmental protection,
  - finally, summarizes the procedure to follow.

Classification of injection products and systems conforms to Annex A (normative) of the standard NF EN1504-5. This standard defines three types (classes) of products or injection systems based on hydraulic binders (H) or polymers (P):

- Class F products, which allow for filling that transmits crack forces, voids, and gaps;
- Class D products, which allow for ductile (elastic) filling of cracks, voids, and gaps, meaning flexible and capable of accommodating subsequent movement;
- Class S products, which allow for expansive filling of cracks, capable of swelling through water adsorption.

Class F products, known as ‘structural injection products,’ are specified to meet principle 4 ‘structural strengthening’ and method 4.5 ‘injection’; products of classes F, D, or S can be used to fulfil principle 1 ‘protection against any penetration’ and method 1.5 ‘sealing’ of a non-structural nature.

A record of these defects should normally be included in the contract documents. However, it must be supplemented by a contradictory record of the condition of the substrates, which also allows for marking and measuring the cracks to be treated and for definitively establishing the means of preparing the substrate to be used. It should be noted that the contradictory assessment of cracks also allows for a rough estimation of the volume of cracks to be injected, thus, deducing the volume of injection material to be used. Most often, the narrow aperture of the cracks to be injected does not provide insight into their internal condition. Therefore, crack cleaning is a delicate operation that must not lead to obstruction. The following means should be available on the construction site:

- equipment for minor chipping (elimination of blisters...)
- brushes and a vacuum cleaner
- oil-free compressed air
- pressurized water (to be avoided if the injection material is sensitive to water)
- heat gun (drying)
- detergents.

Blisters partially masking the cracks must be eliminated through chipping. Cracks should be cleared of all deposits that could hinder their filling, such as dust, mud, traces of calcite, moss, lichens, etc. When the cracks are active, as is the case when a prestressed beam exhibits flexural cracks, injection alone cannot restore the continuity and strength of the concrete material unless followed, for instance, by the implementation of additional prestressing. In such cases, injection represents only a small phase of the work, yet it is essential for successful repair. During injection, the following steps must be taken:

- Firstly, open the cracks to facilitate their filling. Applying a load is the most common method.
- Secondly, avoid any variation in crack aperture during the injection and curing of the injection material to prevent the disruption of forming bonds.
- Finally, wait for the injection material to cure before recompressing the cracks. This can be done first by removing the loads or by using jacks to induce differential displacement at the supports, and secondly by applying additional prestressing. These various operations, which should be planned and detailed in the contract, are further explained below.

Repairing cracks is more challenging than sealing. The heat exchanger is welded for this purpose. The welding is performed using the same material as the unit itself. Heat exchangers in boilers are typically made of copper, less frequently of cast iron, or steel. Aluminium, silicon, manganese, nickel, and zinc are added to the composition. Additional welding requirements include:

- a melting point not lower than 700 °C,
- sufficient viscosity,
- fluidity matching that of a heat exchanger,
- using multiple passes while respecting the thickness of the heat exchanger,
- identifying and eliminating any singularity points in the crack,
- flushing the crack after welding

Copper-zinc welds are considered among the best. They are used to weld most non-ferrous metals with a higher melting point than that of the auxiliary material itself. For human health, solder containing silicon or tin inclusions is safer - up to half a percent. Copper-phosphorus materials are best avoided, and if they are used to weld exchangers, it should be done without mechanical stress, such as shocks or vibrations. A well-chosen solder is half the battle.

Gas burners and torches are used to weld heat exchangers. Before welding, the desired area is cleaned with fine-grit sandpaper and wiped with a solvent-dampened cloth, then heated. The area is heated with a hairdryer or a low-power blowtorch/soldering iron. The key is to reach the temperature corridor and account for subsequent cooling. Welding is preferably in the form of wire or rod: the molten end during welding is fully immersed in adhering flux. If the wire rests too intermittently, or sags onto the exchanger itself, the preheating was insufficient. After work, the weld area is sometimes coated with heat-resistant paint for improved insulation. Over the next two weeks, the integrity of the welded area is checked daily. Engineering services offer mechanical design, analysis, and consulting for shell and tube heat exchangers, as well as air-cooled heat exchangers. The design and analysis of heat exchangers are conducted using software such as PV Elite and Nozzle PRO (FE Pipe module), which are used worldwide. Heat exchangers are designed in accordance with international codes and standards such as ASME BPVC Section VIII Division 1 & 2, TEMA, PD-5500, EN-13445, API-660, API-661, WRCB-107, WRCB-297, WRCB-368, etc., as well as other codes and standards desired by the purchaser.

Examination of mechanical designs of the heat exchanger for compliance with the aforementioned code requirements as well as buyer specifications is also conducted (Fig. 3).

- Fixed tubular plate design according to ASME, PD5500, and TEMA codes.
- Single shell and shell with expansion joints or bellows.
- Stress due to differential thermal expansion of tubes and shell is calculated.
- Design of flanged and duct (thick-walled) expansion joint according to TEMA and ASME.

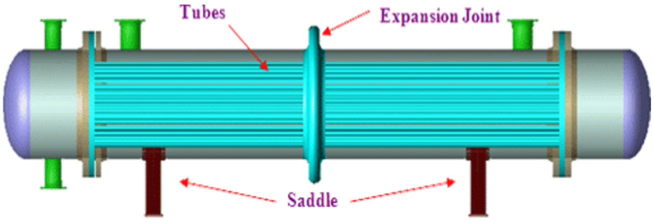


Figure 3. Design of a tubular heat exchanger with an expansion joint.

The two-part bellows are designed to replace the lost thickness in the presence of a crack. They have a thickness of 10 mm and cover the entire affected area. After the successful identification of the crack, the operation is planned to be at 80 % of the warranty. The safety coefficient will then be further increased through the addition and welding of the bellows. Requirements for replacement of expansion joints for the heat exchanger must also be noted:

- The hardness of the tube material must be lower than that of the tubular plate, which is approximately HB30.
- Otherwise, annealing must be performed at a distance of 150 to 200 mm from the end of the pipe.
- For the integrity of welded structures, particular care should be taken to avoid the formation of hydrogen holes within the weld. Hydrogen in the weld primarily originates from moisture in the welding rod, the workpiece, or air.
- At high temperatures, hydrogen decomposes into hydrogen atoms and dissolves a significant amount of liquid metal.
- Once cooled, the solubility of hydrogen in steel diminishes sharply due to rapid weld cooling. Dissolved hydrogen in the metal does not escape, thus forming a hydrogen gas hole.

NUMERICAL STUDY AND SOFTWARE ANALYSIS

Current analyses were performed using finite element software in order to evaluate and assess the performance of composite material as a repair technique. The cracked material used in this investigation is made according to ASTM A285 grade C steel. Tables 2 and 3 present the chemical compositions and mechanical properties of heat exchanger ASTM A285 grade C steel, respectively. Table 4 shows the characteristics of the composite sleeve and adhesive which were used in the numerical data. Figure 4 indicates the dimensions of expansion joint ASTM A285 grade C.

Table 2. Chemical compositions of ASTM A285 grade C steel, /2/.

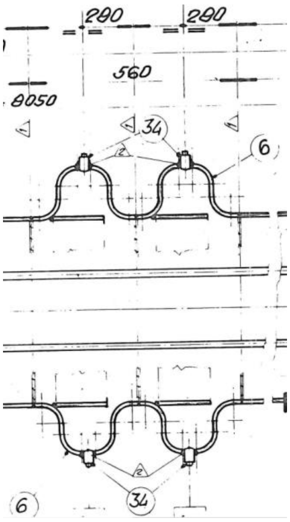
C	Si	Mn	P	S	Al	Cr	Ni	Mo	Nb	Ti	V
0.14	0.24	0.77	0.01	0.006	0.029	0.014	0.01	0.002	0.002	0.002	0.002

Table 3. Characteristics of ASTM A285 grade C, /3-4/, and boundary service conditions.

Property	Young's modulus E (GPa)	Pois. ratio	Ultim. strength σ_{ult} (MPa)	Yield strength σ_y (MP)	Temp. T (°C)	Pressure p (bar)	Expansion displacem. (mm)
Value	119	0.29	380-515	205	250	6	5

Table 4. Characteristics of composite and adhesive, /5/.

		E_1, GPa	E_2, GPa	E_3, GPa	ν_{12}	ν_{13}	ν_{23}	G_1, GPa	G_2, GPa	G_3, GPa
Clock spring	glass/ epoxy	160	25	25	0.21	0.21	0.21	7.5	5.5	5.5
Adhesive	FM73	255			0.32					



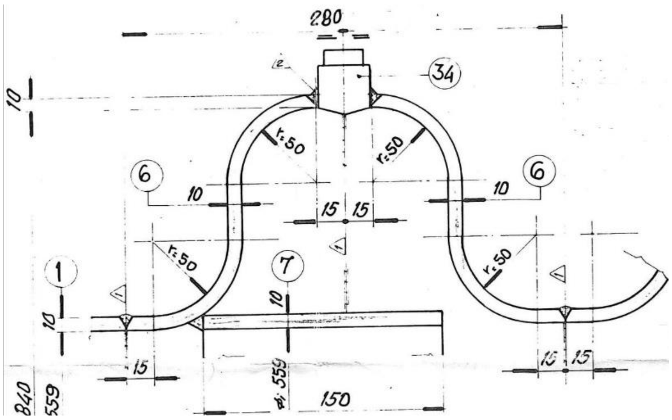
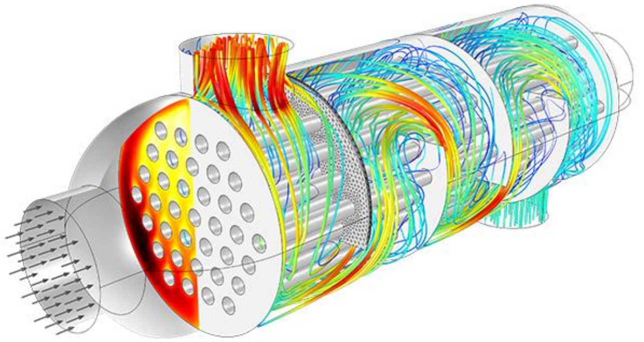
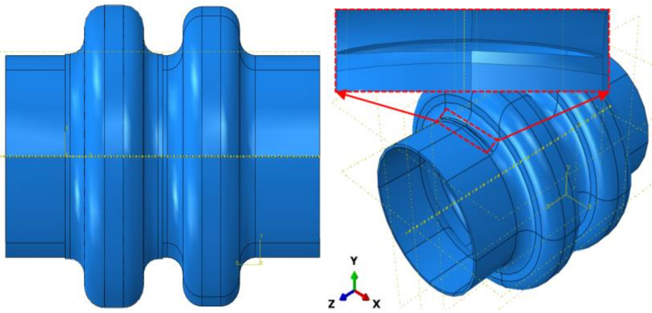


Figure 4. Dimensions of ASTM A285 grade C steel expansion joint.

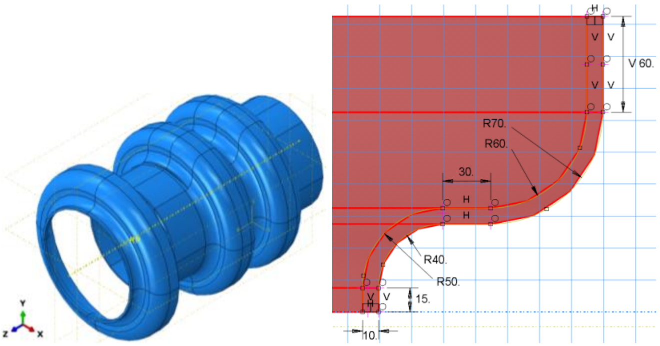
A simple example is presented in Fig. 3 to approve the possibility to analyse the flux in the exchanger by finite element method. The heat exchanger expansion joint is designed as shown in Fig. 5 without other components in order to simplify the calculation and focus on the main position which is cracked. An elliptical defect is created in the joint steel with 300 mm length, 5 mm width, and 10 mm of depth.



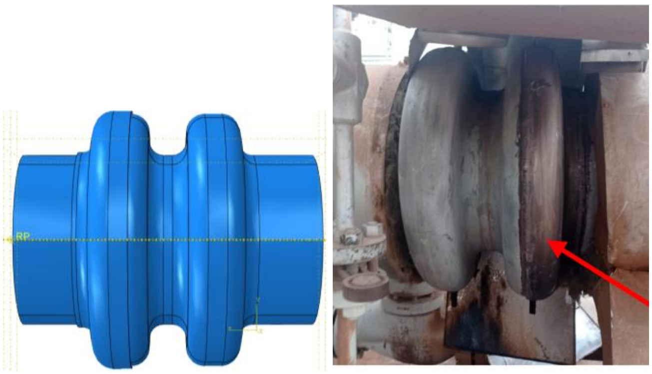


(a) (b)

Figure 5. Expansion joint: a) without defect; b) with defect.



(a) (b)



(c) (d)

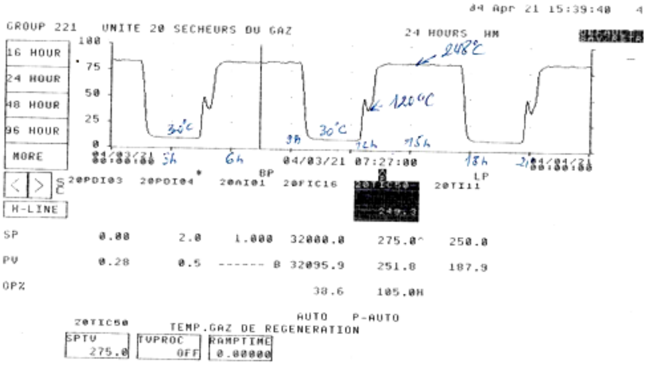
Figure 6. a) Metallic contact design and expansion joint; b) dimensions; c) metallic contact on expansion joint by FE; and d) real metallic contact on expansion joint.

COMPOSITE MATERIAL PROTECTION TECHNIQUE

A composite sleeve is one of the suitable methods for performing equipment structural repair in the petroleum and gas industries. It is chosen due to the following positive characteristics:

- excellent resistance to corrosion, acids, and chemical reactions;
- high strength and stiffness;
- high temperature resistance;
- lightweight;
- low installation and maintenance cost;
- does not mechanically breakdown under ultraviolet (UV) radiation.

Figure 7 shows the evolution of heat in the pipe after and before service. Figure 8 shows basic components of a commercially available composite repair system, Clock Spring® repair system: 1) composite sleeve; 2) interlayer adhesive; and 3) infill material.



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SP      0.00    2.0    1.000    32000.0    275.0^   250.0
PV      0.28    0.5  ------ B 32095.9     251.8    187.9
OP%                               38.6     105.0H

  20TIC50                           AUTO    P-AUTO
               TEMP.GAZ DE REGENERATION
 SPTV        TVPROC      RAMPTIME
    275.0         OFF    0.00000
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Figure 7. Evolution of heat on the expansion joint vs. time.

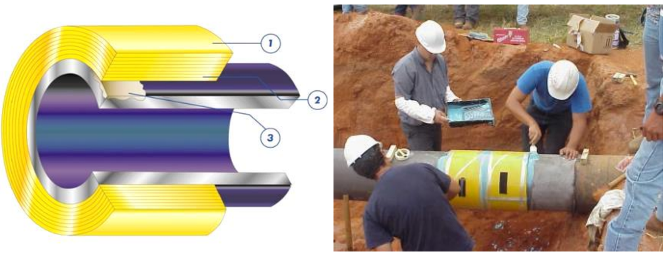


Figure 8. Clock Spring® composite repair system /6-7/.

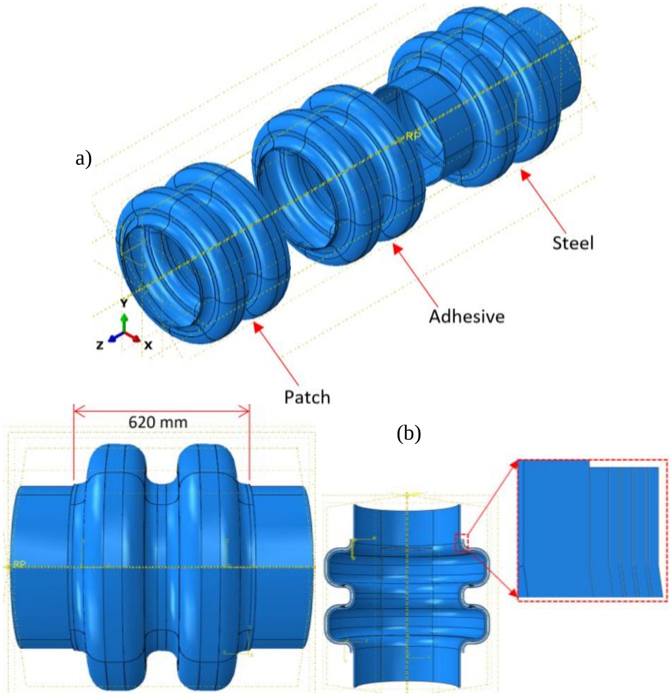


Figure 9. a) Expansion joint, adhesive and patch sleeve; b) expansion joint repair by composite sleeves in contact.

Adhesive is applied to the surface of expansion joint and composite and serves as bonding agent. Grout or ‘putty’ is used as infill material to fill the damaged section in the expansion joint to provide a smooth surface between composite layer and steel, while the composite strengthens the damaged structure by carrying the load. In this type of repair, the load, such as internal pressure carried by tube at the repaired segment is conveyed and shared by outer composite layer through infill material. Thus, the effectiveness of this repair system is largely dependent on the performance of the infill material, /6-7/.

This solution is proposed by some international society to repair the heat exchanger /12/. Figure 10 show an example for this application, FRP Composite Solution Returns Heat Exchanger to Service.

Figure 10. Composite technology strengthens heat exchanger.

A good design basis is central to the successful use of composite repair systems. ASME PCC-2 and ISO 24817 standards have provided for industry a common platform for not only designing composite repair systems but have provided a means for comparing competing composite technologies.

NUMERICAL RESULTS AND DISCUSSION

Repair of some shell and tube exchanger components is possible, but the repair of the expansion joint is very difficult, /8/. In order to see the effects of composite sleeves on expansion joint repair, the software code is used to perform the analysis under real boundary conditions. Generally, Clock Spring (glass/epoxy) and adhesive (FM73) are used in Algerian industries as a repair technique for defective pipelines, /9-10/. The following figures show results obtained by software analyses. The hoop stress is the principal parameter that can affect structural failure. In particular, the elliptical defect was created due to its use in various literature and international standard investigations for pipeline assessment. In order to maintain the material under service, the hoop stress must be less than yield stress.

The hoop stress is the principal parameter that can affect structural failure (Fig. 11). In particular, the elliptical defect was created due to its use in many literature titles and international standard investigations for pipeline assessment. In order to maintain the material under service, the hoop stress must be less than yield stress. The evolution of hoop stresses is presented with and without different sleeve composite on the heat exchanger (Fig. 12). The comparison is proposed regarding the metallic patch presented with the hoop stress in Fig. 13.

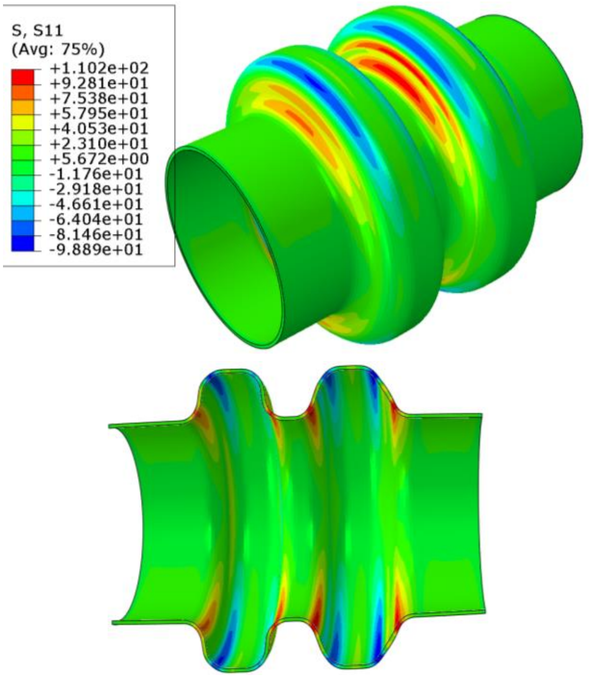
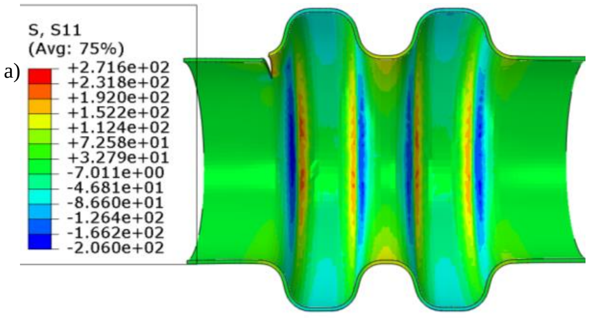


Figure 11. Hoop stress for expansion joint without defect.



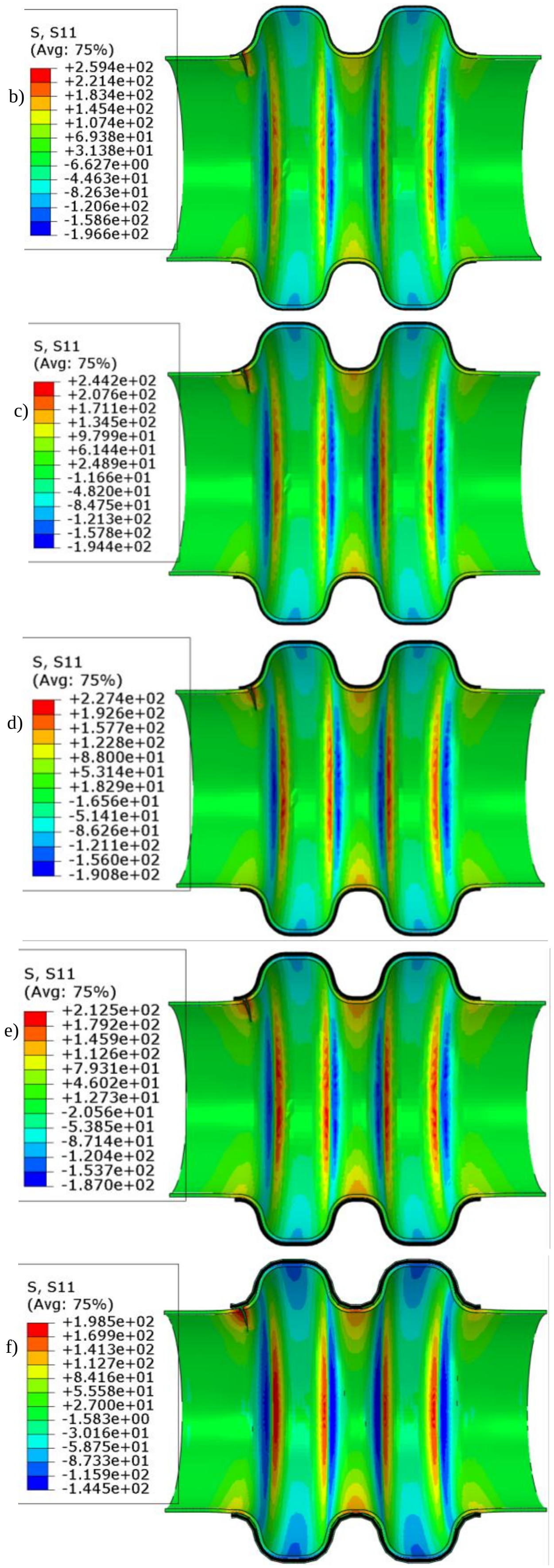


Figure 12. a) Without repair; b) 1 sleeve; c) 2 sleeves; d) 3 sleeves; e) 4 sleeves; and f) 6 sleeves.

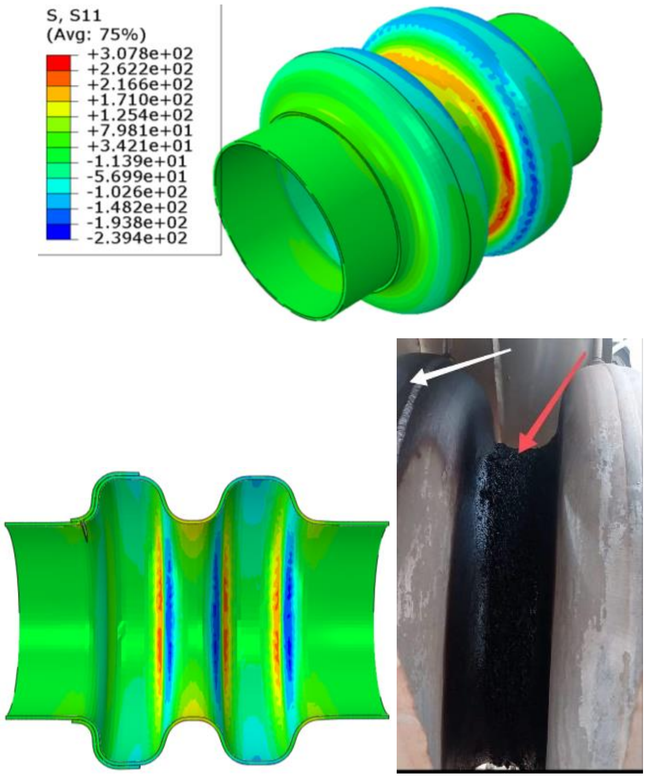


Figure 13. Hoop stress of metallic steel repair.

The FAD exhibits a failure curve as a critical non-dimensional crack driving force k_r vs. critical non-dimensional stress or loading parameter l_r, where $k_r = f(l_r)$. In the plane $[l_r, k_r]$, a failure assessment curve determines the safe (acceptable) and unsafe (non-acceptable) domains. According to ASME B31G, the maximal hoop stress cannot exceed the yield strength of the material, /11/.

If this point is inside the boundary lines of the diagram, limited by the failure assessment curve; the structure is safe Fig. 14. If not, failure occurs, and the assessment point is situated outside of the interpolation curve.

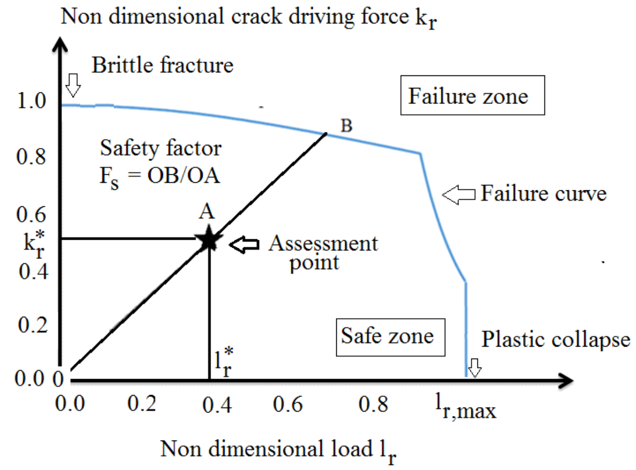


Figure 14. Typical failure assessment diagram (FAD) indicating safe and failure zones, assessment point and safety factor.

In the FAD, the assessment point is denoted A. Due to the definition of parameters k_r and l_r, if crack length remains constant during loading, the loading path is linear from origin to B. Increasing the load until failure allows to reach a failure assessment curve at point B. As illustrated in Fig. 14, the safety factor f_s is defined by ratio OB/OA. This condition is presented in Table 5 and in Fig. 14, where the value of hoop stress decreases with increase of bonded composite. Figure 15 shows that use of 6 composite sleeves puts the expansion joint under safe condition and acceptable for service, while other methods, including metallic contact, are not acceptable for repair.

Table 5. Composite repairs for defective pipes according to ASME PCC-2 and ISO/TS 24817, /7/.

Type of defects	ASME PCC-2	ISO/TS 24817
General wall thinning	Y	Y
Local wall thinning	Y	Y
Pitting	Y	Y
Gouges	R	R
Blisters	Y	Y
Laminations	Y	Y
Circumferential cracks	R	Y
Longitudinal cracks	R	R
Through wall penetration	Y	Y

Y implies generally appropriate.
R implies can be used but requires extra caution.

Table 6. Efficiency of the composite sleeve as a repair technique.

	Hoop stress, (MPa)	Difference % = $(\sigma_{11} - \sigma_y)/\sigma_{11}\times100$	Safety factor Fs = OA/OB
Without defect	110.2	-86.02	2.00
With defect	271.6	24.52	0.60
1 sleeve	259.4	20.97	0.67
2 sleeves	244.2	16.05	0.69
3 sleeves	227.4	9.85	0.74
4 sleeves	212.5	3.53	0.91
6 sleeves	198.5	-3.27	1.09
Metallic steel	307.8	33.39	0.48

Figure 15 shows that use of 6 composite sleeves puts the expansion joint under safe condition and acceptable for service, while other methods, including metallic contact, are not acceptable for repair (see Table 6).

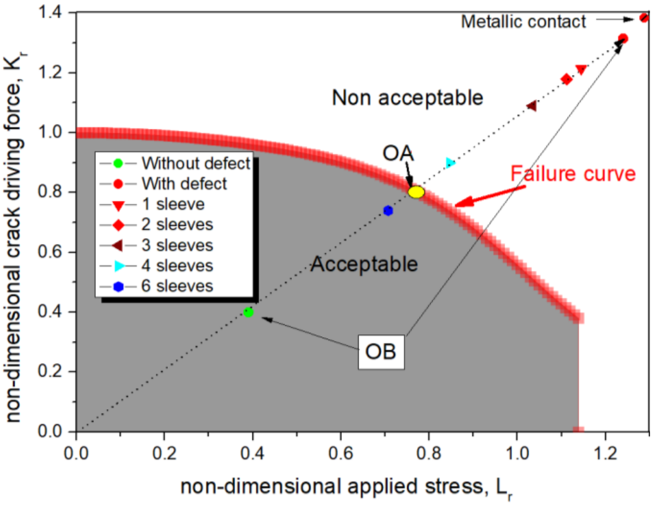


Figure 15. Failure assessment diagram (FAD).

CONCLUSION

We have presented a modern technique to repair a structural defect in the extension joint steel. This technique is called a composite sleeve material. Using a database obtained from the service location, we perform a numerical analysis to estimate hoop stress distribution which is responsible for failure. According to the obtained results, the composite sleeve material is considered as a suitable method for repairing the circumferential crack. In fact, the superior fatigue performance of the composite sleeve material enables to be used in the repair of metallic materials with fatigue damage. Finally, this work confirms that the composite sleeve is considered a suitable technique for repairing expansion joint cracks under high temperature.

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