ANALYSIS OF THE FATIGUE LIFE OF HYDROGEN HIGH PRESSURE TANKS

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ABSTRACT

The present paper aims at studying a high-pressure hydrogen storage vessel, combining a steel liner and a composite reinforcement. Nowadays, this means of storage is notably used in the transport field. However, limits appear insofar as fatigue problem appears when the pressure inside the tank is 700 bar. This matter has to be solved. This study tries to arrange a method to build a 700 bar vessel which could resist to cyclic loading, and particularly focuses on the behaviour of the liner which seems to be the critical element to control. Moreover, as a large part of this gaseous storage is bound to be on board, an optimization of weight is necessary to be competitive.

1 INTRODUCTION

Research for alternative sources of energy to fossil fuels unquestionably is a challenge, economically speaking as well as environmentally speaking. It is obvious that within this context, hydrogen is particularly interesting. It is the most promising source of energy regarding its calorific power and non polluting use. Nevertheless, in order to respond to the economic and environmental criteria, hydrogen production and storage have to be improved.

Hydrogen can be stored as a compressed gas, in a liquid form or in metal hybrids – for instance by using $LaNi_5$. The first type of storage can be realized in four vessels: (a) Type 1 refers to an all metal cylinder, (b) Type 2 is a load-bearing metal liner hoop wrapped with resin-impregnated continuous fibre, (c) Type 3 is a non-load-bearing metal liner - which prevents gas diffusion - wrapped with resin-impregnated continuous filament which is used as a mechanical strengthening piece, and (d) Type 4 refers to a non-load-bearing non-metal liner wrapped with resin-impregnated continuous filament. The fibre is generally a carbon fibre. This work focuses on gaseous storage under high pressure (700 bar) using a type III vessel. The problem with this type of high pressure vessel is the early explosion when it is subjected to cyclic pressures. To solve this problem, the components – steel liner and composite – have to be well-proportioned.

Figure 1: Section of a type III vessel

1.1 Example: 1D case

For a good understanding of the problem, a short presentation on a 1D case is presented. Remarks concerning the latter can be used to solve a 3D case.

1.1.1 Composite

The failure stress of carbon fibre is approximately 3000 MPa with a 2% quasi-elastic strain. In reality, composite is a bi-component carbon/resin. This remark leads to a 2000 MPa failure stress ($\sigma_{failure} \approx 3000 \frac{Volume_{fibre}}{Volume_{resin}} \approx 2000 MPa$) with a 2% maximum strain. The composite behaviour is elasto-fragile.

As far as fatigue is concerned, composite withstand very well, the damage level and the S-N curve (Wolher curve) slope are low. As a consequence, carbon/epoxy composite has a good resistance in fatigue in the direction of fibres.

1.1.2 Metal liner

In this study, the behaviour of the metal liner is elastoplastic and damageable. Contrary to the composite SN curve slope, the one of the metal is more important. For that reason, the critic strain for non-failure decreases with the number of cycles of loadings. One can notice that this phenomenon depends on the type of metal (chemical composition, manufacturing process) and on the temperature of use.

1.1.3 Assembly

Let an assembly compose of metal liner and composite. The two components are supposed to be connected. If this assembly is submitted to a tensile effort, the latter is shared out among both the materials whereas the strain is the same.

For a static loading, composite resistance limits the static resistance of the assembly. Indeed, because of the steel plastification, the majority of the stress is exerted on the composite.

For a cyclic loading, the critical strain of the steel decreases faster than the one of the composite. So, metal strain has a significant effect on fatigue failure on the assembly.

To conclude, for a long fatigue life, one has to reduce the strains during cyclic loading. It can be realized by:

- Transferring the load to the composite to reduce the global strain. That amounts to over-proportioning the static case,
- Or using a metal which has a good behaviour and whose strains do not decrease when it is submitted to cyclic loads.

1.2 Generalization: 3D case

In a vessel study, the loading is less explicit than the uniaxial case presented before. The state of stress is complex insofar as during the loading there are changes of stress direction caused by the elastoplastic behaviour of the metal liner. In this way, it is not easy to predict the stress transfer in fatigue between the two materials. To overcome the risk of a bad stress transfer, the study aims at finding a strain criterion on the metal which allows an infinite lifetime or at least 15000 cycles.

2 ANALYSIS METHOD

The aim of this study is to analyze the behaviour of a tank under fatigue and to optimize the reinforcement by composite. The basis of the optimization is to reduce the strain of the liner in a domain that does not allow a breaking under cyclic loads. This is why, composite has to be well-proportioned to preserve the lifetime of the tank.

To solve this problem, experiments have to be carried out on the steel to have a good approximation of its behaviour. The steel is considered to be elastoplastic and damageable. The characteristics of the steel are determined by a tensile test and cyclic loads on a specimen of the liner. Once the variables determined, a finite element analysis is launched to establish a strain criterion on the steel liner under cyclic loads.
The second step consists in an analytic calculation of the best angles sequence of composite which allows the liner to keep in the strain domain defined before. This computation has been developed according to Chapelle and Perreux method [1]. A pipe made of a metal liner reinforced by composite is studied. The composite is made of polymer reinforced by carbon fibre. The damage of the composite is neglected - because the strain range is very low – and the interface between the liner and the reinforcement is supposed to be perfect. The composite data are given by the manufacturer.

Finally, we will manufacture a type III vessel according to the first and second step study and will exert a cyclic pressure on this HP tank. The aim of this study is to resist 700 bar for 15000 cycles. Comparing resistance tests in fatigue with simulations, the vessel would be optimized successfully.
Figure 2 summarizes analysis and optimization method described above.

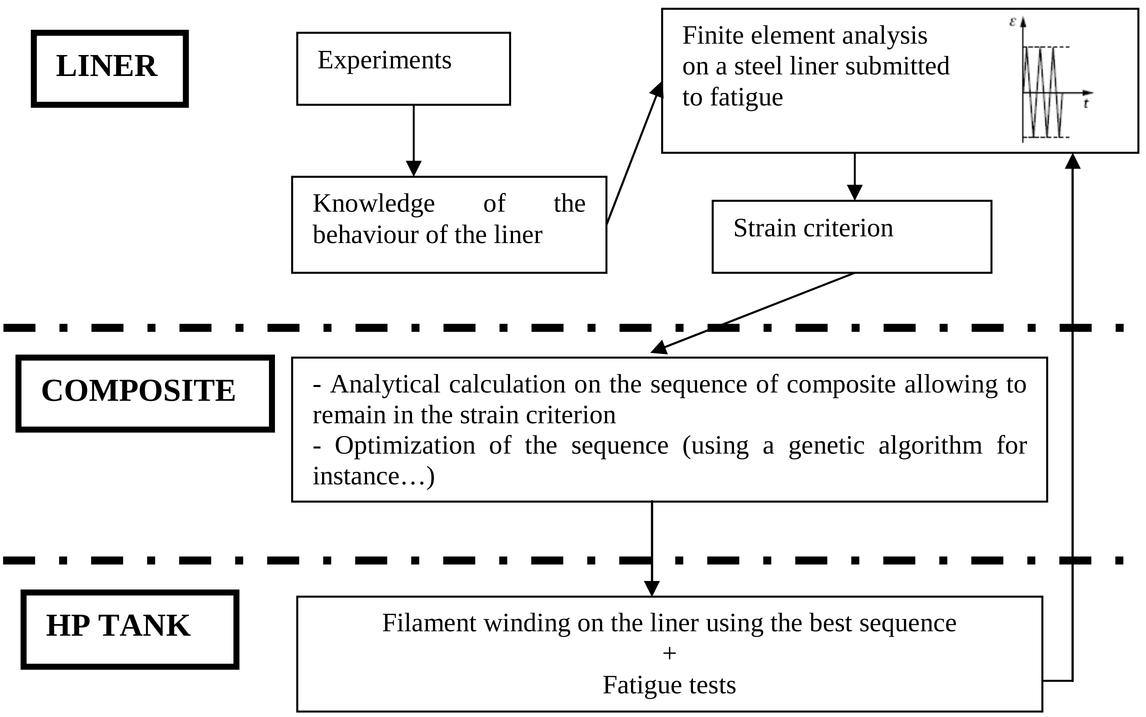

Figure 2: Method of analysis and optimization of the fatigue life of HP tanks

3 Knowledge of the behaviour of the liner

For a better understanding of the behaviour of the liner, a plan of experiments has been defined and is currently in progress:

- Static tests on samples to access to elastic constants such as Young modulus and Poisson ratio, yield strength, tensile strength and breaking stress,
- Cyclic traction/compression on samples with $\frac{\sigma_{\min}}{\sigma_{\max}} = 0$, $\frac{\varepsilon_{\min}}{\varepsilon_{\max}} = -1$ by varying the value of $\sigma_{\max} / \varepsilon_{\max}$ to understand the steel fatigue behaviour [2-3],
- A test with pressure on a metal liner which allows to know, in particular, the evolution of the longitudinal and circumferential strains according to the pressure loading.

First of all, specimens are manufactured from the steel liner by wire Electrical Discharge Machining (wire EDM). The machine - a CHARMILLES ROBOFIL 2510 TW - allows a good precision in dimensions, a high speed of manufacturing (up to 500 mm^2 per minute), and an easy implementation (programming, monitoring of manufacturing). The geometry of the specimens is represented figure 3:

Figure 3: Machining of the specimens by wire EDM

Static tests are carried out on specimens of a vessel. The set up of these tests is realized on a INSTRON 6025 device. The holding of the sample is accomplished by pins. Two extensometers measure the circumferential and longitudinal strains. A finite element analysis is performed to validate the system of prehension (figure 4). On account of two symmetries, the simulation on COMSOL of the static test is conducted on a quarter of the specimen. One can see that the maximum of stress concentration is located on the narrow area, not around the hole. The simulation is suitable with the experiment: the ductile failure is located in the centre of the sample (figure 5). Figure 6 shows the results of the static test. From this experiment, a few constants are evaluated such as the Poisson ratio (ν=0,3), the Young modulus (E=210000 MPa), the tensile strength ($\sigma_R = 928$ MPa), the 0,2% yield strength ($\sigma_Y = 780$ MPa) and a 6% uniform elongation.

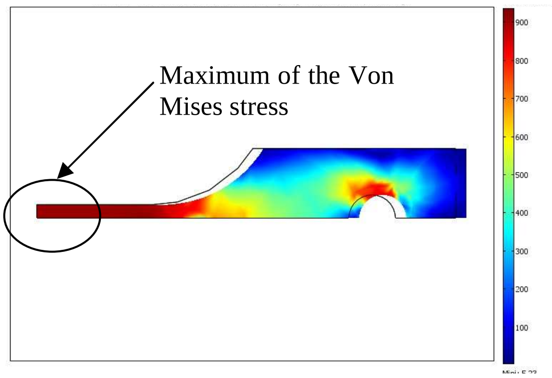

Figure 4: Evaluation of Von Mises stress of a sample

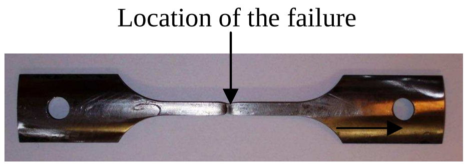

Figure 5: A broken sample

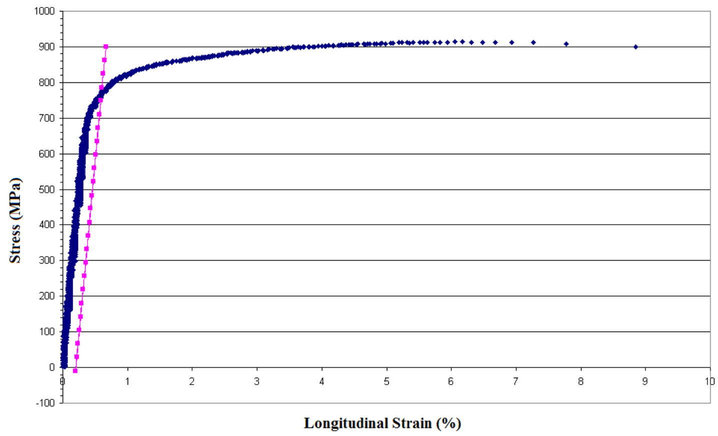

Figure 6: Stress - strain curve for static test

Pins cannot be used for fatigue tests because fatigue amplifies the stress concentration around the hole. A system which hugs inner and outer areas of the extremity of the specimen is manufactured. The whole is positioned between mechanical wedge action grips on a INSTRON 8032 device (Figure 7). Two extensometers measure the circumferential and longitudinal strains. These experiments permit to conclude that a fatigue test with $\frac{\sigma_{\min}}{\sigma_{\max}} = 0$ and $\sigma_{\max}$ between 85 and 90% of the maximum stress allows to resist 15000 cycles.

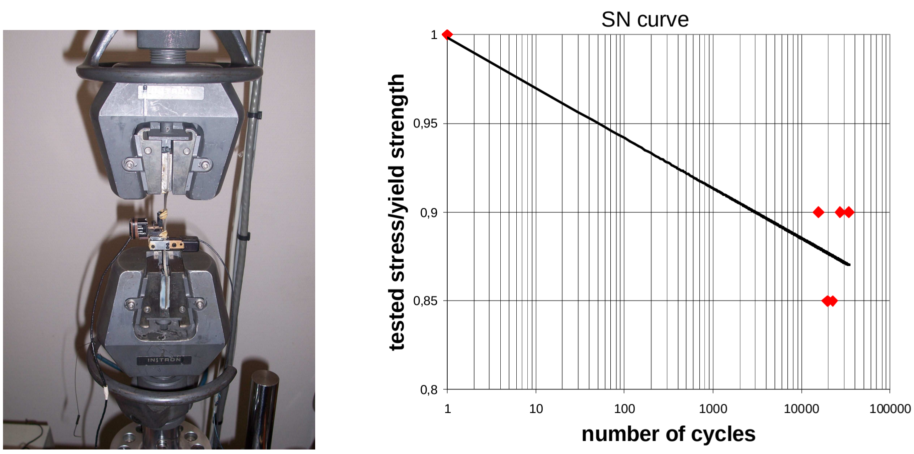

Figure 7: Set up and results of the fatigue tests with $\frac{\sigma_{\min}}{\sigma_{\max}} = 0$

Tests in traction/compression allow to access the variables which define the behaviour of the metal according to Duval works [2]. To reduce the number of trials, a succession of ascending strain stages is carried out on specimens. The aim of this test is to evaluate the necessary number of cycles for a stabilisation in stress. The first conclusion of these experiments is that there is no cyclic hardening/softening and the stress stabilisation is very quick. Over trials will be done with a ratio $\varepsilon_{\min} / \varepsilon_{\max} \neq -1$ to study the effect of the mean strain as far as fatigue lifetime is concerned. As soon as these results are available, a finite element analysis will be carried out by introducing the liner behaviour modelling.
A test of explosion of a vessel gives precious information about the behaviour of the metal by a strain and pressure monitoring along the experiment. Twelve gauges were positioned to measure the axial and circumferential strains: they were glued to the vessel and along the generating line of the vessel.
As it can be seen on picture 8, there is a correlation between the failure mode and the measured strains. Indeed, the maximum of the circumferential strain is located on the failure zone (Figure 8).The value of the latter is approximately 2,8%. At the bottom of the liner, the maximum circumferential strain is 0,5% (Figure 9). The failure zone is located in the cylindrical part of the liner.
This experiment is useful because it gives information about the maximum strains which allow a non-failure of the liner: one has to restrain the circumferential strain under about 1,2% not to have the liner failure during a static loading in pressure. This value is probably lower in fatigue.

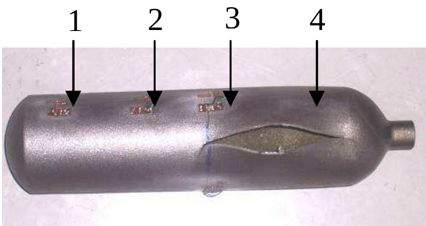

Figure 8: A burst liner

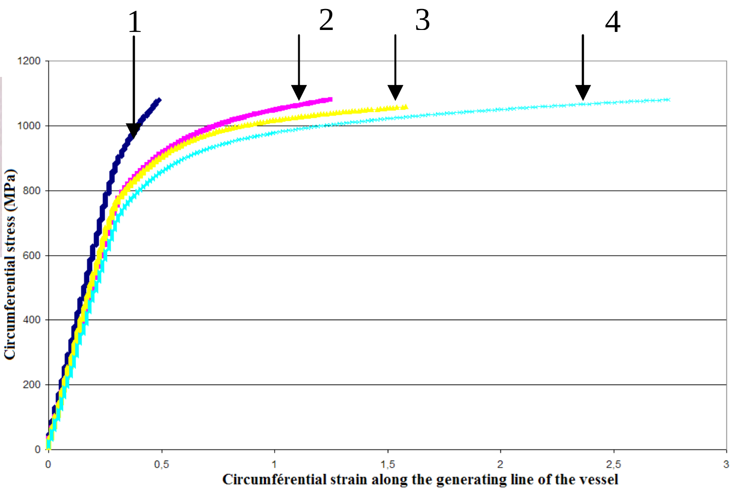

Figure 9: Circumferential strain along the generating line

A finite element analysis – as it was noted on figure 2 - will be made after having the complete database to model the steel. The survey on the sequence of composite is explained below.

4 Determining of the best sequence of reinforcement

Once the strain criterion of the liner is established, one has to find a sequence of composite able to resist and to confine the strains of the liner in this domain. A MATLAB program was devised thanks to –in particular - Chapelle and Perreux work. The damage of the composite is not introduced in the analytic model as it was specified before. The following analysis focuses on the cylindrical section of the hydrogen tank subjected to internal pressure with closed-end effect loading insofar as the failure of the vessel mostly happens in this "middle" part. Figure 10 presents the process of this calculation. Entry variables are those resumed in tables 1 and 2 and the winding sequence around the liner. Output data are displacement/strain/stress for each layer of the composite and of the liner. One can notice that this programme can take into account the liner and its plasticity by considering the liner as a multi-layer. This metal modelling allows to represent the gradual plasticity in the thickness.

The method of calculation of the radial displacement/strains/stresses is not explained in this paper. For further explanations, see [1][4-7]. Nevertheless, Chapelle and Perreux – who works on an aluminium alloy – use the law of Hollomon for fitting the tensile curve [1]. This law is not valuable in the case of steel with a high yield stress σ_Y in comparison with the plastic domain. To have a better modelling, a Ludwick law is introduced: $\sigma = \sigma_Y + K\varepsilon^{\alpha}$. K and α allow to define the plastic behaviour of the liner and are determined from the tensile test curve.
To predict possible failure of the vessel, two criteria were introduced: if the equivalent Von Mises stress σ_{Eq} is higher than the yield strength of the steel or the Tsaï Wu criterion is not respected for the composite, the calculation ends [8].

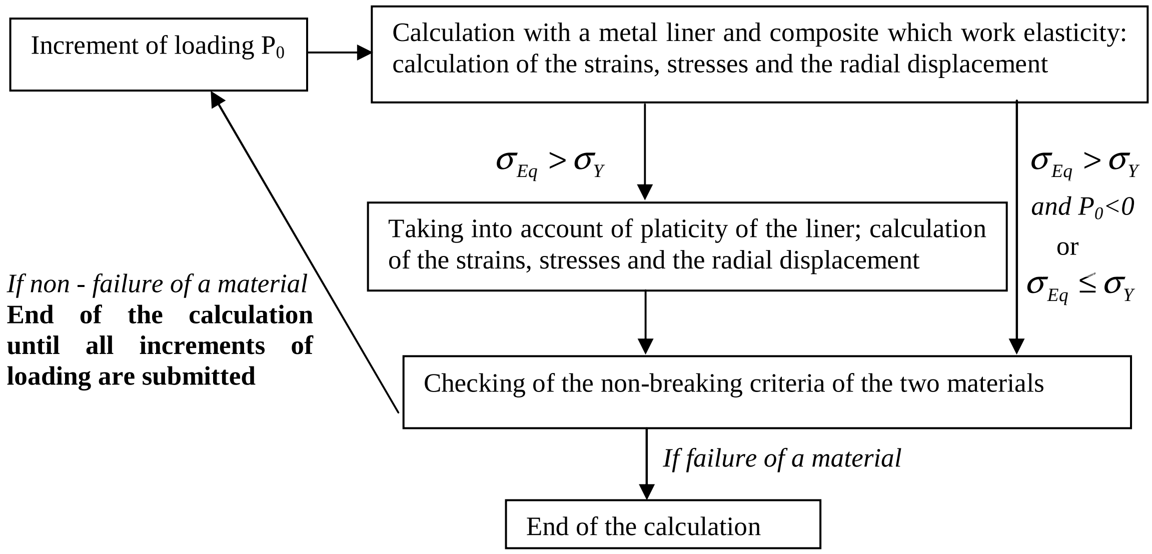

Figure 10: Methodology of calculation

The results of a simulation with a $[+55°,-55°]_2$ stacking sequence are given figure 11. The pressure inside the pipe rises from 0 to 500 bar and then decreases to 0 bar. The loading/unloading speed is 20 bar per second. The inner radius of the liner is 50mm. One can notice that after being submitted to this load, the liner is in compression (figure 11). This state is due to the plasticity of the metal and the fact that composite – which is elastic – wants to return to its initial position.
Thus, knowing the strain criterion of the metal liner, it is easy to find a winding sequence of composite. The best sequence will be found using a method such as a genetic algorithm by minimizing the weight of composite. The consequences of the optimization are a lower weight of the vessel – which is aimed at being board in a vehicle -, a lower time of manufacturing process of the vessel and a lower price in raw materials.

STEEL	
Young Modulus E	210 GPa
Poisson ratio ν	0,3
Yield Strength σ_Y	780 MPa
Tensile strength σ_R	928 MPa
K	1266 MPa
α	0,09
Thickness	2 mm

Table 1: Steel properties

COMPOSITE	
Young modulus of a layer in the fibre direction E_L	150 GPa
Young modulus of a layer in the transverse direction E_T	11 GPa
Shear modulus G	4 GPa
Poisson ratio ν_{LT}	0.27
Poisson ration ν_{TT}	0.49
Tensile strength in the fibre direction	1300 MPa
Compression strength in the transverse direction	1500 MPa
Tensile strength in the fibre direction	50 MPa
Compression strength in the transverse direction	50 MPa
Thickness of a layer	0.25 mm

Table 2: Composite properties

5 Perspectives and conclusion

This study underlines the fact that for a better proportioning of the vessel, the main point to improve is the liner. The first experiments on the steel allowed to complete the database required to the liner modelling but a better knowledge of the steel behaviour is still necessary. Thus, trials on samples with cyclic loadings with a variable ratio $\varepsilon_{min}/\varepsilon_{max}$ and the determining of a strain criterion are the next step of the survey. A tool has been developed to calculate the strains and stress inside a pipe composed of a multi-layer. The later allows, from a defined strain criterion of the steel, to find the best sequence of composite. A work of optimization on the winding sequence of the reinforcement is viewed in order that hydrogen gas storage will be competitive.

6 Acknowledgment

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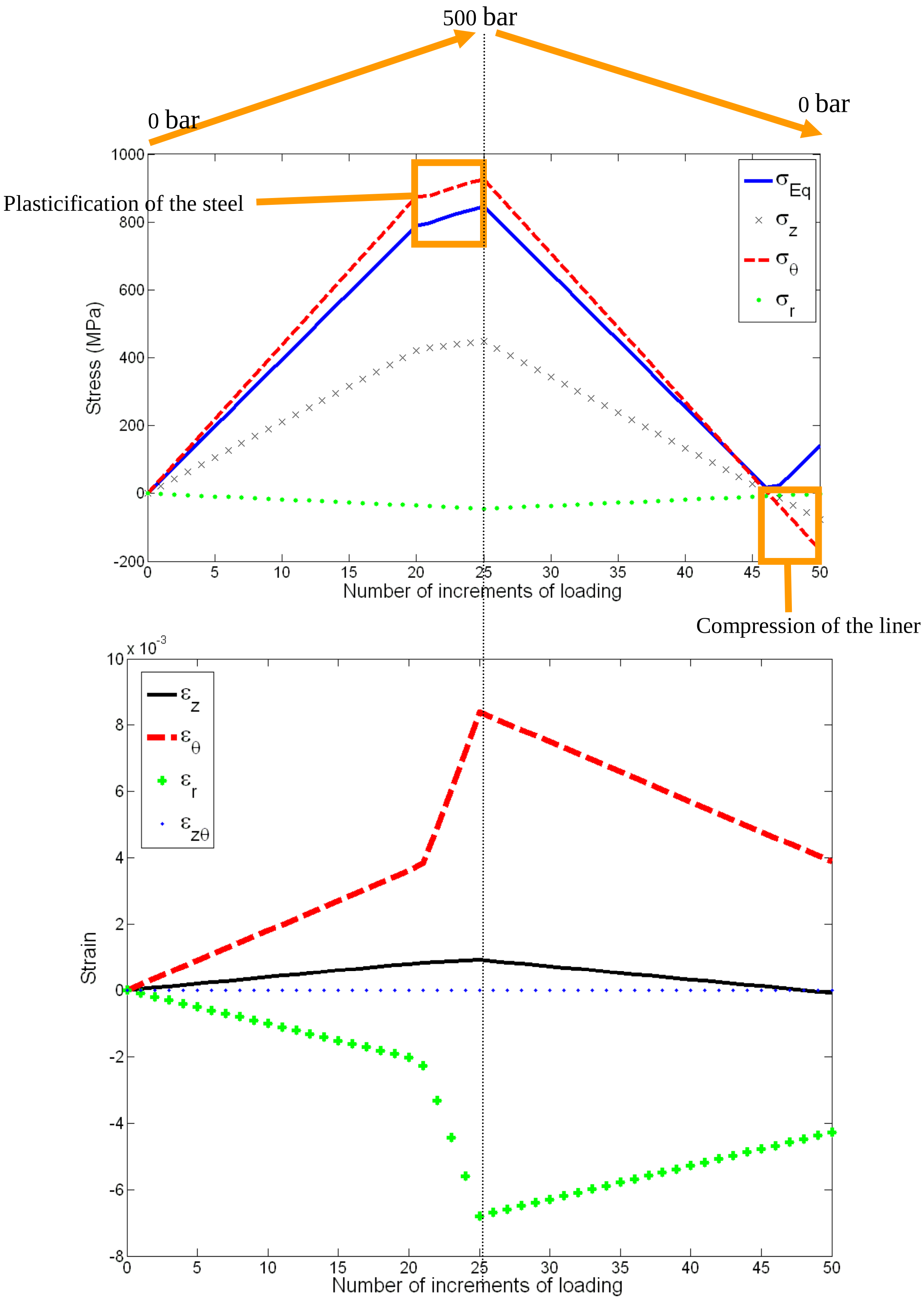

Figure 11 : Evolution of stresses and strains in the mean thickness of the liner under a loading/unloading in pressure