The influence of accidentally appeared stress raisers, on the components lifetime duration

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Abstract. The pipelines for fluids transport have usually to support variable loadings, because of fluid pressure and temperature variation, but also as a result of some environmental effects. On the other hand, some possible errors in the use of equipments and machinery, around the pipes, may lead to accidentally introducing of stress raisers, having different types and sizes, on the pipe surfaces. The presence of stress raisers may lead to significant decreases of pipe lifetime duration. The paper is focused on some fatigue tests, made on specimens that were longitudinally cut from a steel pipe, used for oil transport. Three types of stress raisers were artificially introduced on the specimen surfaces, with spherical, conical, and respectively pyramidal shape, and with three different values of depth (obtained for different levels of down force on the corresponding indenter). The fatigue tests were conducted, using pulsating loading cycles, with the same maximum stress level, situated below the yield point of the steel. The number of loading cycles to failure was established, for each tested specimen, and on this basis it was possible to distinguish the influence of both the type and size of stress raiser, on the remaining lifetime duration, for the studied pipeline.

1. Introduction

The strength of mechanical parts can be strongly affected by the presence of stress raisers, both in static and dynamic loading regime. For the static case, the elastic stress concentration effect is considered as the concentration coefficient $K_t = \sigma_{\text{max}} / \sigma_n$, the ratio of the maximum (experimentally measured, or analytically/numerically estimated) and the nominal (calculated) stress values from the respective transverse section of the studied body. The value of that coefficient is not influenced by the material of the body, or by the loading level; in fact, it depends on the stress raiser geometry, the type of loading and the nominal stress character. It is important to note that the use of $K_t$ is not amenable when local plastic strains are detected into the studied material.

It is easy understandable that the presence of a stress raiser into a member structure is affecting its fatigue resistance, so it is interesting to quantify the influence of the shape and size of stress raiser on the material response to fatigue tests. The studied parameter could be the fatigue limit, i.e. the lower stress level that, after an established cycle number of variable loading, determines a micro crack to nucleate and then to grow, leading to the final material failure.

2. The stress concentration effects, on the fatigue materials response

A possible method for observing the stress concentration influence, on the fatigue resistance of a material, can be based on a pre-determined value of $K_t$ (suitable with the stress raiser geometry and the
proposed type of loading), together with the durability curve $\sigma_a-N$, that is obtained for specimens (of the studied material) without any stress raiser on their surfaces [1]. One can draw a theoretical durability curve, corresponding to a specimen (with the same type of loading) containing a stress raiser of the proposed type, simply by dividing to $K_t$ the stress values of the initial curve (see figure 1) [2]. Unfortunately, the results of that simple method are not usually confirmed by the experimental data, which usually lead to a durability curve $\sigma_a N$ that is placed above the initial curve, but below the theoretical one. One can assume that the stress raiser influence on the fatigue resistance of the studied material is less important that the measure indicated by the static stress concentration coefficient $K_t$. As a consequence, its use in fatigue calculus design could lead to unacceptable errors. In its place, an effective stress concentration factor $K_f$ must be determined, having appropriate values for the real variable loading situation, and the proposed type of stress raisers.

$$K_f = \frac{\sigma_R}{S_R}$$

where $\sigma_R$ is the fatigue limit for the stress raiser free specimen, and $S_R$ is the fatigue limit for the specimen that includes on their surfaces the proposed type of stress raiser. The effective coefficient is usually established for symmetric loading cycles. One can observe the definition similarity, for both $K_t$ and $K_f$ coefficients, with the important difference that $K_t$ is the ratio of two stress values, while $K_f$ is based on two fatigue limit values (corresponding to the same durability of the studied mechanic part).

It is interesting to note that $K_f$ is very closed to $K_t$, for big values of the tip radius of stress raiser; on the other hand, for small values of tip radius, one can observe that $K_f<<K_t$, probably because of the material yielding, into the stress raiser vicinity, during the cyclic loading. The corresponding plastic strains that occur into material could lead to an effective maximum local stress level that is not as much as $(K_t\sigma_a)$, the estimated value, when assuming an elastic material response [3].

Some effects of this kind are observable for most of the engineering metals, for high stress levels of cyclic loading, i.e. for short lifetime duration of the mechanic parts [4]. For very ductile metals, those effects could be observable even for long lifetime duration. On the other hand, the plastic strains are negligible, or even absent, for most of the materials, even for fatigue limits of $10^6$ to $10^7$ cycle numbers. It is also possible for the material to be less sensitive to the peak stress values, and more influenced by an effective maximum stress value, at a distance from the point of the maximum load.

![Figure 1. Examples of theoretical and experimental durability curves.](image-url)
In order to characterize the concentration effect of a given stress raiser, a *notch sensitivity* coefficient is calculated as follows:

\[ q = \frac{K_f - 1}{K_t - 1} \]  

(2)

When \( K_f = K_t \), that coefficient is \( q = 1 \), and one can assume that the intensity of stress raiser effect is at the maximum possible level; the \( q \) value decreases with \( K_t \) and \( q = 0 \) (the stress raiser has no effect) for \( K_t = 1 \). It was established that the notch sensitivity coefficient is influenced by the material nature, and it is proportionally increasing with the tip radius of stress raiser. For certain materials, as steel, it was observed that \( q \) also increases with the material ultimate tensile strength (UTS).

An empirical relationship (a simplified form of Neuber relation) is also used for that coefficient:

\[ q = \frac{1}{1 + \beta \rho} \]  

(3)

For steels having UTS \( \leq 1500 \text{MPa} \), the material constant \( \beta \) can be calculated as [5]:

\[ \beta = \frac{1.7}{\text{UTS}} \times 10^{386} \]  

(4)

For low or intermediate lifetime duration, some important yielding levels could be detected into ductile materials volume, and so the local stress level \( \sigma_n \) is lower than \( K_r \sigma_a \). As a consequence, the fatigue resistance ratio – for specimen with and without stress raiser – is lower than \( K_r \); it must be replaced by a new stress concentration factor \( K'_f \), which value depends on the number of loading cycles until the specimen failure:

\[ K'_f = \frac{\sigma_{as}}{\sigma_{as}} \]  

(5)

One can assume that, for ductile materials, the value of \( K'_f \) decreases from the \( K_f \) level, that correspond to parts having high lifetime durations, to approximate 1, for low lifetime durations.

### 3. The samples from fluids transport pipelines

The pipelines that are used for the transport of fluids (as oil and gas) may often be damaged on their surfaces. Supervision and control of the pipeline network operation are complex activities, because of the large number of input-output nodes that must keep at certain controlled levels some parameters as pressure, flow, temperature, and so on. The pipelines are usually placed on large territories, where some risk factors may affect their proper functioning and integrity. For detecting such possible events, the pipeline network operation is monitored, by analyzing the variation of some standard parameters values. By consequence, it is possible to early detect the presence of some undesirable events such as spills, blocking valves, defects of metering devices, etc. A crack in a pipe within such a transport system could obviously lead to significant losses. On the other hand, it is well known that the maintenance operations may sometime lead to the appearance of some artificial stress raisers on the pipes surfaces, possible affecting their lifetime duration. Such stress raisers could be very different in size and shape, and it is important to analyze their influence on the pipeline lifetime duration [6].

In this regard, some tensile specimens were processed (see figure 2), according to the prescriptions of ISO 6892 Standard Test Method, from a steel pipe with an external diameter of 246mm.

The pipe material was OLT 35 (without an ISO correspondent) or DIN ST35.8 P235GTH, having the chemical composition as follows:
In order to establish the limits of elastic deformability for the studied steel, a static tensile test was conducted, using one of the above described specimens; the stress-strain curve and the mechanical characteristics of the material were obtained as follows:

|                        | Extension at Tensile Strength (%) | Load at Tensile Strength (kN) | Tensile strain at Tensile Strength (%) | Tensile stress at Tensile Strength (MPa) |
|------------------------|----------------------------------|--------------------------------|----------------------------------------|------------------------------------------|
| 1                      | 17.85158                         | 23504.46569                   | 0.17921                                | 425.45144                                |

|                        | Energy at Break (Standard) (J)   | Load at Break (Standard) (%)  | Extension at Break (Standard) (%)      | Tensile stress at Break (Standard) (MPa) |
|------------------------|----------------------------------|--------------------------------|----------------------------------------|------------------------------------------|
| 1                      | 245.06220                        | 3975.72617                     | 25.27805                               | 0.25048                                  |

|                        | Tensile stress at Yield (Standard) (MPa) | Tensile strain at Yield (offset 0.2 %) (Ext/mm) | Load at Yield (Offset 0.2 %) (kN) | Displacement (Strain %) at Yield (Offset 0.2 %) (mm) |
|------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------|---------------------------------------------------|
| 1                      | 777.19716                                | 269772.08911                                 | 1699.24816                       | 0.08372                                           |

|                        |                        |                                                               |                                   |                                                   |
|------------------------|------------------------|----------------------------------------------------------------|-----------------------------------|---------------------------------------------------|
| 1                      | 0.00331                | 329.67118                                                     | 0.00331                           | 51.38800                                          |

|                        |                        |                                                               |                                   |                                                   |
|------------------------|------------------------|----------------------------------------------------------------|-----------------------------------|---------------------------------------------------|
| 1                      | Rectangular            | 100.00000                                                      | 2.92203                            | 17.40300                                          |

Figure 2. The specimen appearance, for static and cyclic loading tests.

Figure 3. The stress-strain curve and data table, as resulting from static tensile test.

Figure 4. The specimens (with or without stress raisers) for static and cyclic loading tests.

4. Fatigue tests results
A pulsating cycle type was used (having the asymmetry coefficient R=0), as testing loading cycle that was intended to have only elastic stress parameters. As a consequence, the maximum stress level (\(\sigma_{\text{max}} = 321\text{MPa}\)) was established to be placed below the value of tensile stress at yield (329MPa) from
above, for all the fatigue tests. Using the specimen cross-section area, a corresponding maximum load of $F_{\text{max}}=16\text{kN}$ was permanently used in the experiments.

Three types of stress raisers were artificially obtained on every specimen frontal surface, by pressing on it with an indenter of a suitable shape, i.e. spherical, conical or pyramidal. The main differences between them are given by the presence or absence of a sharp tip or, respectively, of sharp edges. The final appearance of the specimens is above presented in figure 4, indicating for each the type (or the absence) of stress raiser, and the respective indentation load.

For each of the indenter shapes, three different levels of down force were used – $45\text{kN}$, $30\text{kN}$, and $15\text{kN}$ – in order to obtain three categories of sizes for the corresponding stress raisers. As it was estimated, as a result of the fatigue tests, with pulsating loading cycles, and $F_{\text{max}}=16\text{kN}$ ($\sigma_{\text{max}} = 321\text{MPa}$), different numbers of loading cycles to failure were obtained, for the above presented specimens. The following figure 5 presents the typical aspect of failure cross-section (which was permanently coincident with that of stress raiser), for the three type of specimens.

**Figure 5.** The three type stress raisers appearance, before and after the fatigue failure of the specimens.

5. **Results and comments**

As it was previously described, three categories of stress raisers were artificially obtained, on the surface of some specimens taken from a steel pipe. Different numbers of loading cycles to failure were obtained, as a result of fatigue testing (with an equal level of maximum stress $\sigma_{\text{max}}$), but a similar manner of specimen failure – located into the cross-section where the stress raiser was placed. One can assume that both the shape and size of stress raiser exert an influence on the lifetime duration of tested specimens. It is important to note that some of the exploitation conditions of pipelines can be treated as variable loading, leading to fatigue effects on the pipe material.

The influence of stress raiser size on the number of loading cycles to failure may be evaluated using as a dimensional parameter the dislocated material volume, as a result on the indenter pressing on the specimen surface. The stress raiser occurrence is obviously accompanied by a certain level of local plastic strain in the superficial material. One can understand that some pipeline maintenance operations may introduce, on the pipeline surfaces, some stress raisers of that kind.

The Table 1 from below presents, for each type of stress raiser ($h=$stress raiser depth; $a=$the spherical cap radius, or the con radius, or the pyramid side, each of them being measured at the specimen surface), the values of dislocated material volume ($V$) and the corresponding number ($N$) of loading cycles to failure.

Those data can be used for drawing a graph of variation for the number of cycles to failure, in dependence with the dislocated material volume (as a result of stress raiser accidental appearance), for some fatigue tests having the same maximum stress level (321MPa); three graphs of that kind are presented in figure 6, for the above presented types of stress raisers.
One can assume that, for every type of stress raiser, the increase of dislocated material volume leads to a decrease of number of cycles to failure; the maximum decreasing rate was obtained for the pyramidal stress raiser (that has many sharp edges), the minimum rate – for the spherical one (that is characterized by smooth surfaces).

Each of the three curves from above was approximated by a logarithmic variation, in order to establish the number (N) of loading cycles to failure, using as a reference the same value of dislocated material volume (V); for example, choosing V=10mm$^3$, the results for N are presented below (see Table 2 from below).

**Table 1.** The dislocated material volume and the corresponding number of cycles to failure

| Stress raiser type | a [mm] | h [mm] | V [mm$^3$] | N    |
|-------------------|-------|-------|-----------|------|
| Spherical         | 3.40  | 1.33  | 25.46     | 36264|
|                   | 2.70  | 0.79  | 9.32      | 85696|
|                   | 1.85  | 0.35  | 1.93      | 125663|
|                   | 3.00  | 1.73  | 16.32     | 46960|
| Conical           | 2.60  | 1.50  | 10.62     | 55737|
|                   | 1.55  | 0.89  | 2.25      | 79502|
|                   | 6.43  | 2.59  | 35.88     | 20953|
| Pyramidal         | 4.20  | 1.69  | 10.02     | 44301|
|                   | 3.53  | 1.42  | 5.95      | 53839|
| No stress raiser  |       |       |           | 146000|

**Table 2.** The number of loading cycles to failure for V=10mm$^3$

| Stress raiser type | N    | N$_{WOC}$/N$_{WOC}$ |
|--------------------|------|----------------------|
| Spherical          | 82700| 1.76                 |
| Conical            | 59880| 2.43                 |
| Pyramidal          | 45950| 3.17                 |
| No stress raiser   | 146034|                     |

The value in the last column can be considered as a *coefficient of cycle number reduction*, and it is obtained by dividing two numbers of cycles to failure – corresponding to some specimens without...
(NWOC), respectively with (NW sharing) stress raisers on their surfaces. The biggest value (namely 3.17) of that coefficient was obviously obtained for the pyramidal stress raiser.

One may assume that, using that sort of experiments and results, an evaluation of number of loading cycles to failure could be made, for a real pipe with an accidentally introduced stress raiser on its surface, by dividing the number N corresponding to the stress-raiser-free specimen, with the reduction coefficient from above (having in view the stress raiser real shape, and for every 10mm³ of dislocated material volume).

The reduction coefficient may also be obtained (for different dislocated material volumes and for each stress raiser shape that was studied) by using the calculus relationship from figure 6.

6. Conclusion
The possibility of estimating the lifetime duration for the pipelines for fluids transport is very important, in order to prevent some catastrophic events that could lead to damages, environmental harm or even to loss of human lives. On the other hand, one can imagine that various incidental factors, as environmental effects or possible errors in the use of equipments and machinery, may introduce on the pipe surfaces some defects acting as stress raisers of different shapes and dimensions. Their appearance may lead to a significant decrease of lifetime duration, for the affected pipeline. In many practical situations, the immediate repair or changing of a pipe is not possible, so it is necessary to quantify the stress raiser possible influence on the pipe lifetime duration, and to approximate the remaining service life of the pipe. The present paper was focused on the influence of stress raisers type and size, on the lifetime duration of a steel pipeline, having an exterior diameter of 246mm, and a wall thickness of 3mm. Some tensile specimens were cut longitudinally from the pipe wall, and three types (spherical, conical and pyramidal) of stress raisers were artificially introduced on the specimens’ frontal surface. Three values of depth were obtained, for each type of stress raiser, using different levels of down force on the corresponding indenter that was applied on the specimen surface. Some fatigue tests, with pulsating loading cycles, having the same maximum stress level (321MPa – i.e. a value that was situated below the yielding point of the pipe material); as a result, the number of loading cycles to failure was established for each type of specimen. A decrease was observed, for that number, for each of the stress raiser type, with the increase of dislocated material volume. The decreasing rate increases, from the spherical to conical and then to pyramidal stress raiser. One can assume that the coefficient of cycle number reduction may be used, in order to approximate the remaining service life of the studied pipeline.

7. References
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