Comparison of the most harmful defects present in a steel pipe that can cause fatigue failure

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Abstract. Steel pipes used for conveying pressurized fluids are often defective due to manufacturing error, improper handling or construction materials. These defects may be in the form of cracks which propagate until the mechanical structure is fractured, or in the form of dent which produce a local concentration of stress and thus weaken the structure. In this paper, we will present a numerical model for estimating the accumulation of damage that takes into account the effect of the loading history. This model will be used to evaluate the harmfulness of a dent on the one hand, of a semi-elliptical crack on the other hand. These defects will be considered to be present in a metal tube subjected to internal pressures caused by the water hammer phenomenon. A parametric study will make it possible to conclude the most harmful defects among the defects studied.

1. Introduction

Over the last 50 years, demand for energy has steadily increased and oil and gas transmission pipelines have become important networks for transporting large amounts of pressurized fluid over long distances [1]. In order to improve the profitability of this mode of transport, manufacturers are increasing the operating pressure and the pipe diameter [2]. From 1910 to 2000, the diameter of the largest pipelines increased fourfold and the transport pressure increased sixty times.

As with any other structure, failure can occur in in-service oil transport steel pipelines. However, due to good design guidelines, materials and operating practices, transmission pipelines may have a comprehensive safety device.

The safe operation of the pipeline and its high reliability depend on various factors, such as: mechanical damage or external interference, fatigue cracking, material defects, welding cracks, inadequate welding, internal or external corrosion, and the aging of the physical condition of the pipeline metal and welded joints. Damage from human error or vandalism is also not unusual [3, 4].

In the oil industry, damage resulting from contact with foreign objects is often referred to as mechanical damage. Defects in the pipeline may occur in a number of forms. A combination of two or more defects is also common [5]. To ensure proper monitoring of the safe operation of these structures, tools are used to assess the harmfulness of defects [6]. These tools depend on the types of defects and failure modes. Limit analysis is generally used for the assessment of non-severe defects such as corrosion defects or dents [3]. In the case of serious defects such as cracks in welds, sharp notches or a combination of a dent and a notch, a mechanical fracture approach is usually used.

Previous work has been carried out by the authors on the study of the main defects that are likely to exist in the pipes, in particular those due to impact with a foreign body (dent), welding (crack in the
welded area) and corrosion [7-9]. The results of these analyzes made it possible to identify the most dangerous defects which could lead to the rupture of metal pipes under pressure. Several numerical models have also been developed which allow the determination of the harmfulness of the defect most commonly encountered in metal pipes under internal pressure.

These works have shown that the most harmful dent defect is the one which has a rectangular shape oriented longitudinally with respect to the pipe with unconstrained configuration. Unconstrained dent is a dent caused by a foreign body that has been removed after impact. For the harmful crack defect, it is a longitudinal semi-elliptical crack present in the internal wall of the pipe. The parameters of the dent defect are presented in figure 1 and those of the crack are presented in figure 2.

![Figure 1. Dent parameters.](image1)

![Figure 2. Crack parameters.](image2)

In the previous studies, cracking and indentation defects are investigated separately. In this paper, a model estimation of the damage caused by the defect in the pipe is applied to both of these defects in order to conclude on the most harmful defect. This numerical damage assessment model, which takes into account the loading history, is presented.

The pipes considered in the parametric study are subjected to internal pressures caused by the water hammer phenomenon (figure 3). High levels of dynamic loading, such as water hammer pressure waves, make the defect even more damaging [10]. The range of defect dimensions used in this numerical model is that encountered in practice.

![Figure 3. Water hammer wave pressure induced by an abrupt change in fluid velocity.](image3)

2. Material and methods

Fatigue loading of pipe structures varies by nature. During fatigue loading, the material in the pipeline undergoes alterations resulting in damage [11-12]. It is therefore essential for models to take explicit account of the variability of fatigue loading [13].

To this end, authors have proposed a nonlinear model for fatigue damage accumulation [9]. It’s based on the work of Thun et al. [14]. The effect of the load interaction is considered in this numerical model. The algorithm for this numerical model is shown in Figure 4. Cumulative damage under
variable amplitude loading levels may then be estimated. The leakage or rupture of the structure is to be achieved when the cumulative damage is equal to the unit.

It should be noted that this algorithm is to be adapted to the type of defect being studied (dent or crack). The fatigue life estimation model for the dent case uses as additional parameters the dent depth \((d/D_0)\) and the endurance limit of the material \((\sigma_D)\). If the studied defect is a crack, then the model for estimating the fatigue life takes as an additional parameter the dimension of the crack \((a/c)\), the constants of the law of Paris \((C\text{ and } m)\) and the critical stress intensity factor \((K_{IC})\). Details on these two models are provided on [7] and [8].

![Damage accumulation model](image)

**Figure 4.** Damage accumulation model that takes into account load history.

This model takes the parameters of the pipe, the defect as well as the internal load as inputs. The material used is steel API X52 and its mechanical properties are shown in Table 1. The dimensions of the pipe can be seen in Figure 5.

**Table 1.** Mechanical properties of API X52.

| Parameter         | Value       |
|-------------------|-------------|
| Young modulus E   | 200 GPa     |
| Poisson’s ratio \(\nu\) | 0.3         |
| Yield strength \(\sigma_y\) | 410 MPa    |
| Ultimate tensile strength \(UTS\) | 498 MPa    |
The pipe is subjected to an internal pressure of variable amplitude as shown in Figure 6. Pressure peaks are caused by a water hammer phenomenon following a sudden change in the valve state (opening/closing) controlling the transport of water in the pipe. This curve is produced using a characteristic method. Details of the calculation are available in [8].

3. Results and discussion

The damage accumulation model is validated in a previous study led by authors [9]. The results provided by this model are presented in figure 7 and figure 8.

For the calculation of the deviations, let us take as a reference the value of the number of failure cycles obtained for the dimension of the defect immediately below (example: the value of the result obtained for the penetration of the depth \( d/D_0 \) of 20 per cent is compared to that of 17.5 per cent).

Figure 7 shows a deviation of -40.2, -29.1, -22.9, -18.6, -13, -12.3 and -11% for \( d/D_0 \) dent depth of 5, 7.5, 10, 12.5, 15, 17.5 and 20%, respectively. This shows that the deeper the defect, the more harmful it is. One can also notice that the \( d/D_0 \) parameter varies exponentially with the number of cycles.

From figure 8, one notice a deviation of 167.2, 73.2, 54.4, 37 and 34.5% for cracks of dimension \( a/c \) of 0.5, 0.6, 0.7, 0.8 and 0.9, respectively. This shows that the higher the ratio, the less harmful the defect. It is also noticeable that the \( a/c \) parameter varies exponentially with the number of cycles.
Figure 7. Damage accumulation for pipe presenting an unconstrained longitudinal dent.

Figure 8. Damage accumulation for pipe presenting an internal longitudinal crack.

By simple reading and comparing the curves of figures 7 and 8, it can be seen that the shape of the evolution curve of the accumulation of damage is more curved for crack defects. A low number of cycles can cause a large variation in damage towards the end of the life of the pipe. This phenomenon is much more accentuated in the case of pipes with semi-elliptical crack defects located on the inner surface of the pipe in the longitudinal direction than in the case of pipes with a rectangular longitudinal dent with an unconstrained configuration.

Figure 9. Number of cycles according to the dimensional parameters of the defects studied.

To better compare the two types of defects, one will retain the values of the number of cycles to fatigue and put them on the same scale. The result of this process is shown in Figure 9. This figure can make it possible to approach the equivalence in terms of harmfulness due to two different types of defects. For example, for the defects studied and from a reading of this figure, one can say that a dent defect of $d/D_0=7.5\%$ is equivalent in terms of harmfulness to a crack of $a/c=0.55$. It can also be concluded from this figure that, among the cases studied, the crack defect is more harmful than the dent defect.
4. Conclusion and perspectives
A nonlinear numerical model for estimating damage accumulation, taking into account the effect of the loading history, was presented. This model has been previously developed and validated by the authors and is used in this paper to study the effect of the presence of a defect in a steel pipe. Two defects are studied: an unconstrained longitudinal dent and a semi-elliptical internal crack. Each of these two defects represents the most harmful defect of its type. A parametric study concluded that:

- The increase in the number of pressure cycles causes more fatigue in a structure with a crack defect than with the same structure with a dent defect;
- In the cases studied, it has been found that the crack defect is more harmful than the dent defect.

The developed numerical model makes it possible to find equivalence between two different types of defects in terms of harmfulness. In future work, it will be used to classify the most important defects that may be present in a steel pipe subjected to water hammer pressure waves.

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