FATIGUE BEHAVIOUR OF POLYPROPYLENE FOR AUTOMOTIVE APPLICATIONS

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Abstract The fatigue behaviour of semi-crystalline polymers is a key issue for many engineers who have to calculate more and more components for structural applications. Many studies focused on the fatigue crack behaviour but there is a lack of data in the field of multi-axial fatigue and especially for non-cracked components in the long life regime. After describing the experimental device, fatigue tests results are presented and analyzed using standard multi-axial fatigue criteria. Crossland and Sines criteria are compared showing that semi-crystalline polymers are much more sensitive to the mean hydrostatic stress than to the maximum hydrostatic stress.

1 INTRODUCTION

The fatigue behaviour of semi-crystalline homopolymers is crucial for the design of polymer-based structural applications. Such materials exhibit a complex behaviour due to time-dependent mechanisms. Scientific literature about this issue widely focused on crack propagation approaches, mainly based on tension-compression experiments [1-3] performed to compare materials. Only a few works were carried out about high-cycle fatigue approaches. Therefore only a very few data are available on multi-axial high-cycle fatigue behaviour of polymers [4].

The mechanical properties of the investigated polypropylene (PP) are briefly presented first. Then the paper is divided into the 3 following sections.

- The first part presents the special experimental device developed for the multi-axial testing of the material.
- The second part presents experimental results: S-N curves are depicted and analyzed for both tension and torsion loading.
- The third part is devoted to the mechanical analysis of experimental results by the mean of multi-axial fatigue criteria. Basic fatigue criteria (i.e. Crossland and Sines criterion) are tested and a modified expression of the Sines criterion is finally proposed.

2 EXPERIMENTAL DETAILS

2.1 Experimental device

A special experimental device has been developed in the laboratory for the multi-axial fatigue testing of thermoplastics. As illustrated in Figure 1, fatigue samples were thin extruded pipes clamped down by special grips used to perform tests under tension, torsion or combined loading on the same sample. This allowed obtaining all results on the same material i.e. elaborated from a fixed process and for a given geometry.

In the present study, temperature was measured by the mean of three thermocouples, all at the middle-height of the pipe. Two thermocouples were located at the inner and outer surface of the specimen, and the third one measured the temperature of the air inside the pipe. A compressed air cooling system was used to maintain the temperature of the air inside the pipe at the room temperature. The axial strength and displacement, as well as the torque and angular displacement were recorded at the same time as temperatures.

2.2 Material

The material was a non-reinforced polypropylene (PP) for automotive applications. It is a semi-crystalline thermoplastic exhibiting a crystallinity ratio of 41%, glassy transition temperature at about 10°C and melting temperature at 166°C. These results were obtained from Differential Scanning Calorimetry (DSC) experiments performed under N_2 sweep at 10K/min in a TA Instrument DSC-2920 apparatus. The weight fraction extent of crystallinity χ was calculated as follows: $\chi = \Delta H_f (T_m) / \Delta H_f^0 (T_m^0)$ where $\Delta H_f(T_m)$ is the enthalpy of melting measured integrating the melting peak and $\Delta H_f^0(T_m^0)$ is the enthalpy of melting of the fully crystalline polymer at the equilibrium melting point (149 J/g [5]).

3 FATIGUE TEST RESULTS

All fatigue tests were carried out with a triangular signal, at a constant frequency of 1Hz and at load controlled constant amplitude. The triangular signal was chosen for constant strain-rate purpose because of the viscosity of the material. Different load ratios R were applied : -1 and 0.

3.1 Tension

The S-N curve obtained under tension at R = -1 is presented in Figure 2 on a linear-log scale. No significant temperature raise was observed during tests performed at the lowest stress amplitude. These pipes did not fracture. For tests leading to a low number of cycles to failure, the temperature increased by a 3° to reach a nearly constant value after 300 cycles, and drastically increased again in the last 100 cycles should appear as given in Figure 3.

The tension fatigue limit σ_D (here for 10^5cycles and $\sigma_D = \sigma_a$ with $\sigma(t) = \sigma_m + \sigma_a \sin\omega t$) in such conditions (triangular; 1Hz; R = -1) is arbitrary normalized to 1 for further comparison. Following this normalization, the experimental value of the tension fatigue limit in another condition (triangular; 1Hz; R = 0) is 0.46 according to the Figure 2. This last result proves that the mean stress has a significant influence on the fatigue limit.

3.2 Torsion

S-N curves under torsion are presented in Figure 4 with a linear-log scale. The evolution of the temperature in torsion was strictly the same as in tension. Pipes submitted to the lowest stress amplitude did not fracture. The fatigue limit in torsion τ_D seems difficult to estimate from the S-N curves shown in Figure 4. If existing, it is expected to be lower than measured in tension. The normalized values would be about 0.55 at R = -1 and 0.3 at R = 0. Like in tension, these tests suggest an influence of the mean shear stress. This result is very important because it is not the case on metallic materials.

4 MULTIAXIAL FATIGUE CRITERION

Some existing initiation fatigue criteria (i.e. Crossland and Sines criterion) were used to analyze lifetime results from the previously presented multi-axial tests. Due to the low frequency of 1 Hz, such tests are very time consuming. For this reason, additional tests based on the Luong's method [6] were also carried out to determine the fatigue limit using one sample only. This method is used for some metallic materials and gives interesting results [7]. We tried to apply the following methodology to polymeric pipes to get the fatigue limit under different multi-axial conditions at R = -1. According to this method, the pipe was loaded at a given stress amplitude (below the estimated fatigue limit) for 500 cycles, the temperature was recorded at the end of the 500-cycle stage. The same sample was loaded again at higher stress amplitude for 500 cycles more with a temperature measurement again at the end of the 500-cycle stage. This procedure was repeated up to the pipe failure. At the end of the test, Figure 5 can be plotted and the fatigue limit is supposed to be given by the intersection of the two linear regimes.

The fatigue limit given by the Luong's method :

- In tension at R = -1 is 10 % to that estimated from the S-N curve.
- In tension at R = 0 is 41 % to that estimated from the S-N curve.
- In torsion at R = -1 is 27 % to that estimated from the S-N curve.
- In torsion at R = 0 is 33 % to that estimated from the S-N curve.

Values obtained from the two methods in tension at R = -1 were close, but are rather different in tension at R = 0 and in torsion at R = -1 and 0. The accuracy of the intersection determination may account for this difference. Even if this is a first step that must be largely completed by other tests for different conditions, it suggests that this method would be of interest for fast estimation of the fatigue limit in such material; it can't be a good experimental procedure to determine the fatigue limit.

Several tests were performed in torsion and tension at different normalized mean stress levels. Regardless of the loading path, fatigue limit values show a mean stress influence, as evidenced in the previous section from the S-N curves.

Finally, tests results obtained on Table 1 and Table 2 are analyzed using three multi-axial criteria : Sines (1), Crossland (2) and a Sines-modified one (3) :

$$\sqrt{J_{2,a}} + \alpha_{Si}\,\sigma_{H,moy} \leq \beta_{Si} \quad \text{with} \quad \beta_{Si} = \tau_{-1} \quad \text{and} \quad \alpha_{Si} = \frac{\tau_{-1} - \sigma_0/\sqrt{3}}{\sigma_0/3} \tag{1}$$

$$\sqrt{J_{2,a}} + \alpha_{Cr}\,\sigma_{H,\max} \leq \beta_{Cr} \quad \text{with} \quad \beta_{Cr} = \tau_{-1} \quad \text{and} \quad \alpha_{Cr} = \frac{\tau_{-1} - \sigma_{-1}/\sqrt{3}}{\sigma_{-1,\max}/3} \tag{2}$$

$$\sqrt{J_{2,\max}} + \alpha_{Si,\mathrm{mod}ified}\,\sigma_{H,moy} \leq \beta_{Si,\mathrm{mod}ified} \quad \text{with} \quad \beta_{Si,\mathrm{mod}ified} = \tau_{-1} \quad \text{and} \quad \alpha_{Si,\mathrm{mod}ified} = \frac{\tau_{-1} - \sigma_{0,\max}/\sqrt{3}}{\sigma_0/3} \tag{3}$$

where $J_{2,a}$ is the amplitude of the second invariant of the stress tensor, $\sigma_{H,m}$ the mean value of the first invariant of the stress tensor, $\sigma_{H,\max}$ the maximum value of the first invariant of the stress tensor and $\sigma_{H,\max}$ the maximum value of the first invariant of the stress tensor. α and β of each criterion can be calculated with two given fatigue limits. In the case of fatigue limit obtained by S-N curve (Table 1) two results are used to validate the different criteria. In the case of fatigue limit obtained by Luong's method (Table 2) ten results are used to validate the different criteria. For all experiments, Figure 6 and Figure 7 present the scatter between the predicted fatigue limit and the experimental value obtained from the S-N curve and Luong's method. The first comparison (S-N curve, figure 6) is the reference to compare the different criteria because experimental results to determine the fatigue limit are good. The second comparison (Luong's method, figure 7) is not really reliable (up to 41 % error with S-N curve) but ten results are used to compare the three criteria. Between those ten results, the one obtained at load ratio R = -1 is more accurate than those obtained for mean stress different from -1. Only results exhibiting a scatter lower than 20% are interesting to be discussed.

(i) For loading cases without any mean shear stress, the Sines and Sines-modified criteria are the most accurate.

(ii) For loading cases with a mean shear stress, the Sines-modified criterion is the most accurate.

Provided that the mean stress influence pointed out by Luong's method is relevant, the criterion (3) is a basic modification of the usual Sines criterion that takes into account the mean stress influence on the torsion fatigue limit. This experimental result is important because this effect is not observed in metallic materials. Tests with a classical S-N curve would be useful to get a clear conclusion on that subject.

5 CONCLUSIONS

Several conclusions arise from the presented work.
- Under fatigue loading, the behaviour is influenced by the hydrostatic stress.
- The determination of the fatigue limit using temperature measurement with Luong's method gives estimation of the fatigue limit with up to 40 % error compare to S-N curve.
- The fatigue limit under torsion is influenced by the mean shear stress. This result is important because it is not the case on metallic materials.
- Comparison between Sines, Crossland and the Sines-modified criterion shows that the fatigue behaviour of semi-crystalline polymers seems to be governed by the mean hydrostatic stress more than by the maximum hydrostatic stress. Furthermore, the maximum shear stress is probably a predominant governing parameter in comparison to the amplitude (the fatigue limit in torsion depends on the mean shear stress).

6 ACKNOWLEDGEMENTS

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7 REFERENCE LIST

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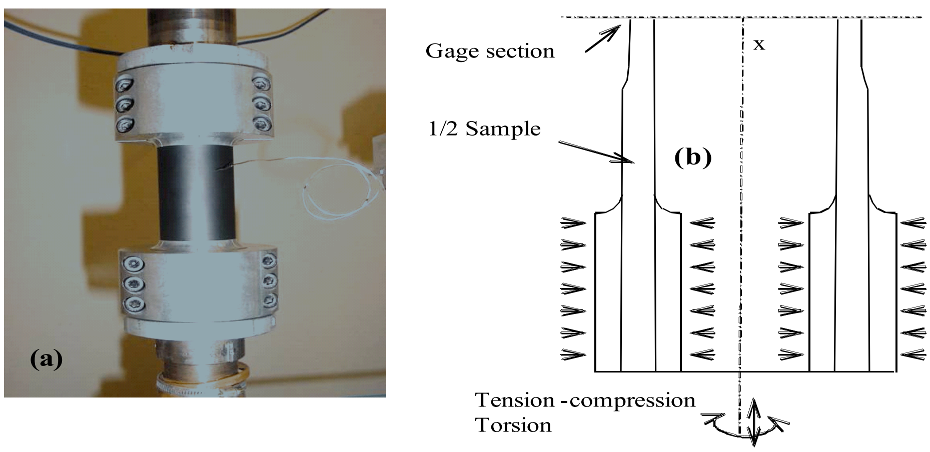

Figure 1 : Experimental device (a) : general view with contact temperature measurement by thermocouple
(b) Detail of the grip system

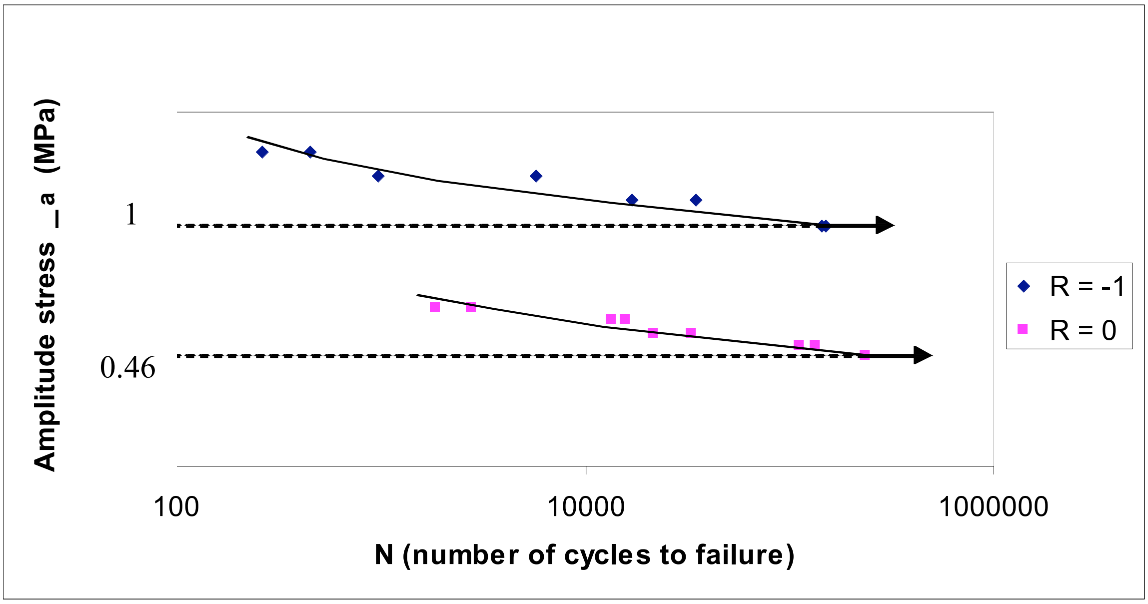

Figure 2 : S-N curve under tension loading R = -1 and R = 0

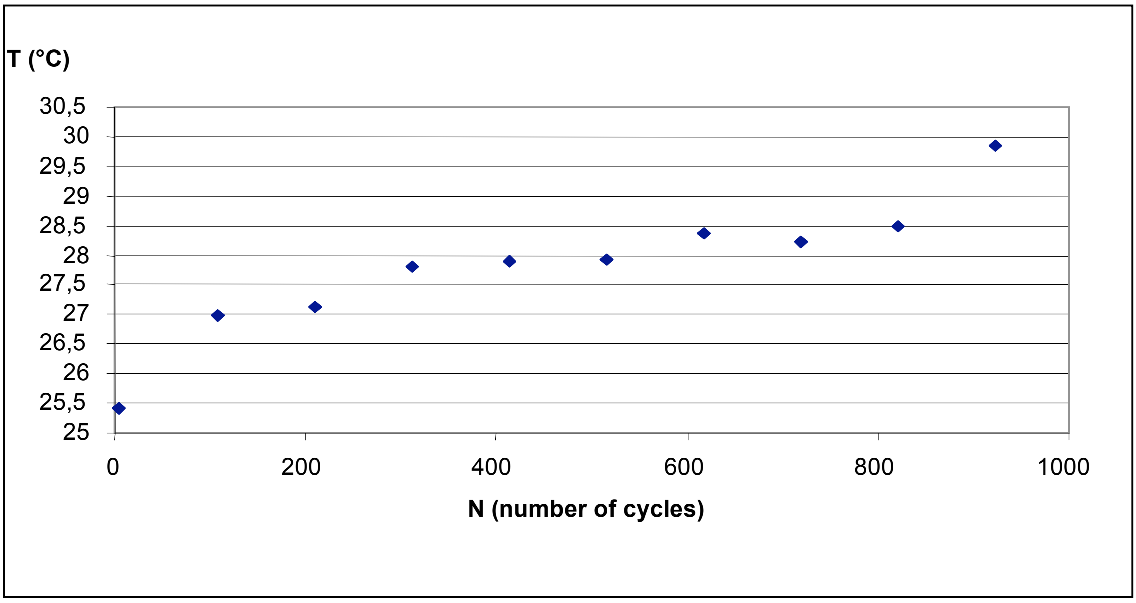

Figure 3 : Evolution of the temperature of pipe according to a number of cycles

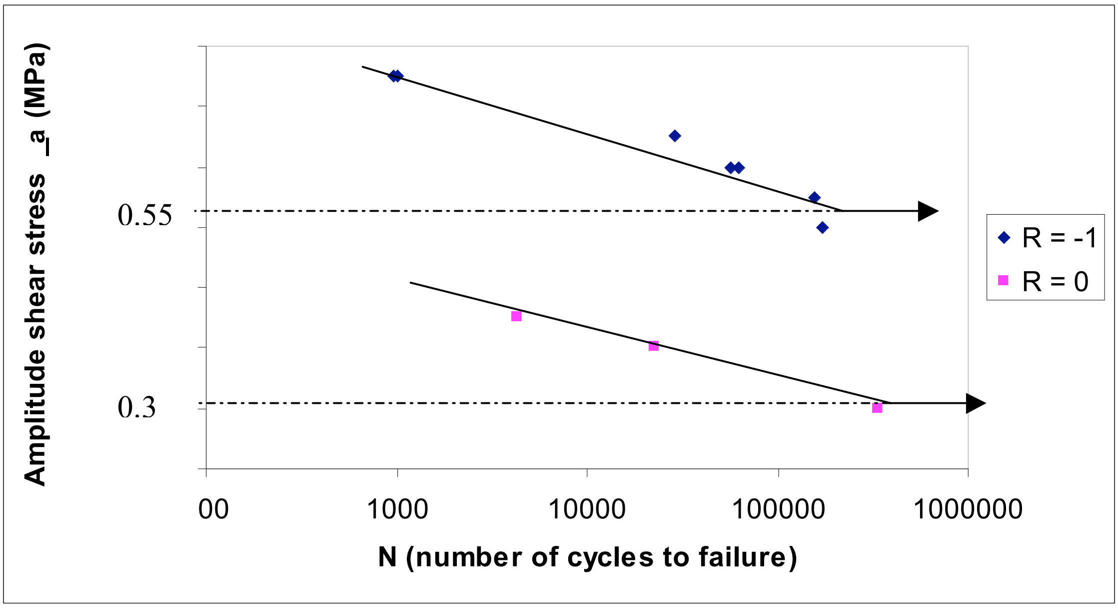

Figure 4 : SN curve under torsion loading R = -1 and R = 0

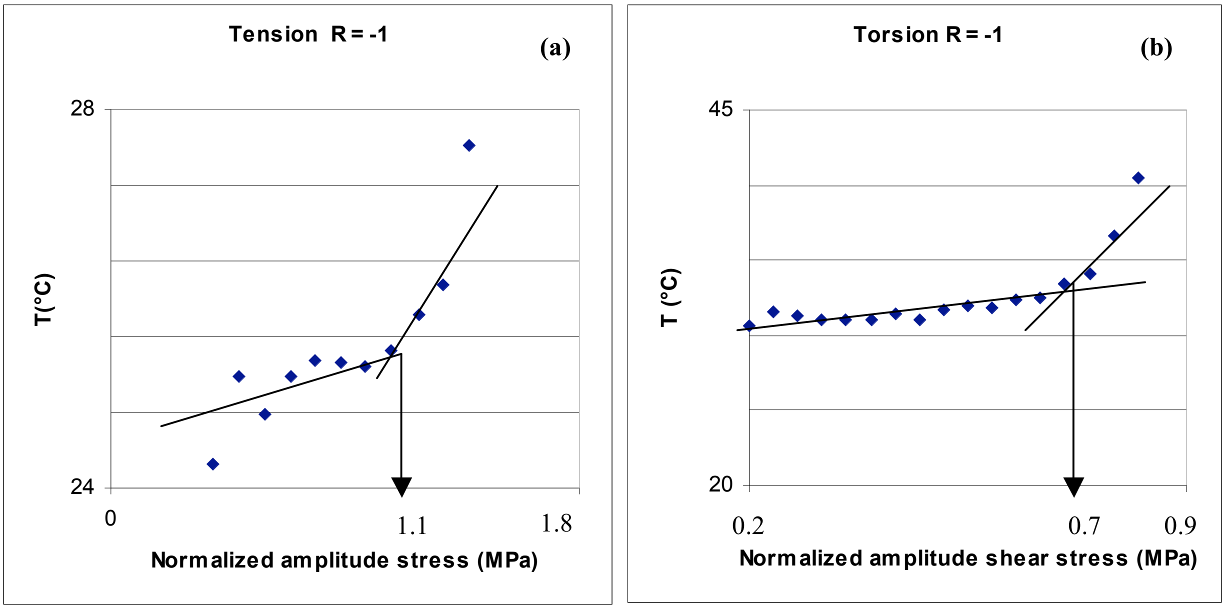

Figure 5 : Fatigue limit determination using temperature measurement [2]
(a) under tension (b) under torsion

N°	Type of loading	σ_{moy} (MPa)	σ_a (MPa)	τ_{moy} (MPa)	τ_a (MPa)
1	Tension R = -1	0	1	0	0
2	Tension R = 0	0.46	0.46	0	0
3	Torsion R = -1	0	0	0	0.55
4	Torsion R = 0	0	0	0.3	0.3

Table 1 : Experimental fatigue limit results for different combined test by S-N curve

N°	Type of loading	σ_{moy} (MPa)	σ_a (MPa)	τ_{moy} (MPa)	τ_a (MPa)
1	Tension	-0.32	1.1	0	0
2	Tension R = -1	0	1.1	0	0
3	Tension	0.32	0.9	0	0
4	Tension R = 0	0.65	0.65	0	0
5	Tension	0.97	0.35	0	0
6	Torsion R = -1	0	0	0	0.7
7	Torsion R ≈ 0	0	0	0.37	0.4
8	Torsion	0	0	0.51	0.26
9	Torsion	0	0	0.59	0.11
10	Tension/Torsion R = -1 ; $\sigma = 0,25\ \tau$	0	0.15	0	0.59
11	Tension/Torsion R = -1 ; $\sigma = 0,5\ \tau$	0	0.26	0	0.51
12	Tension/Torsion R = -1 ; $\sigma = 0,75\ \tau$	0	0.44	0	0.59

Table 2 : Experimental fatigue limit results for different combined test by Luong's method

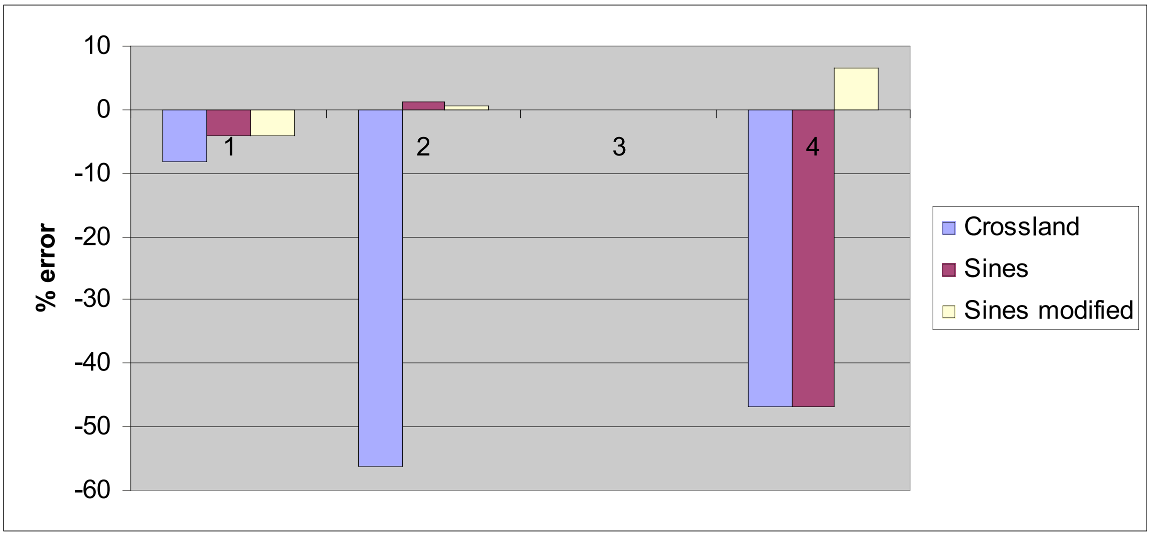

Figure 6 : Comparison between Sines, Crossland and Sines modified criterion
(experimental fatigue limit obtained by S-N curve)

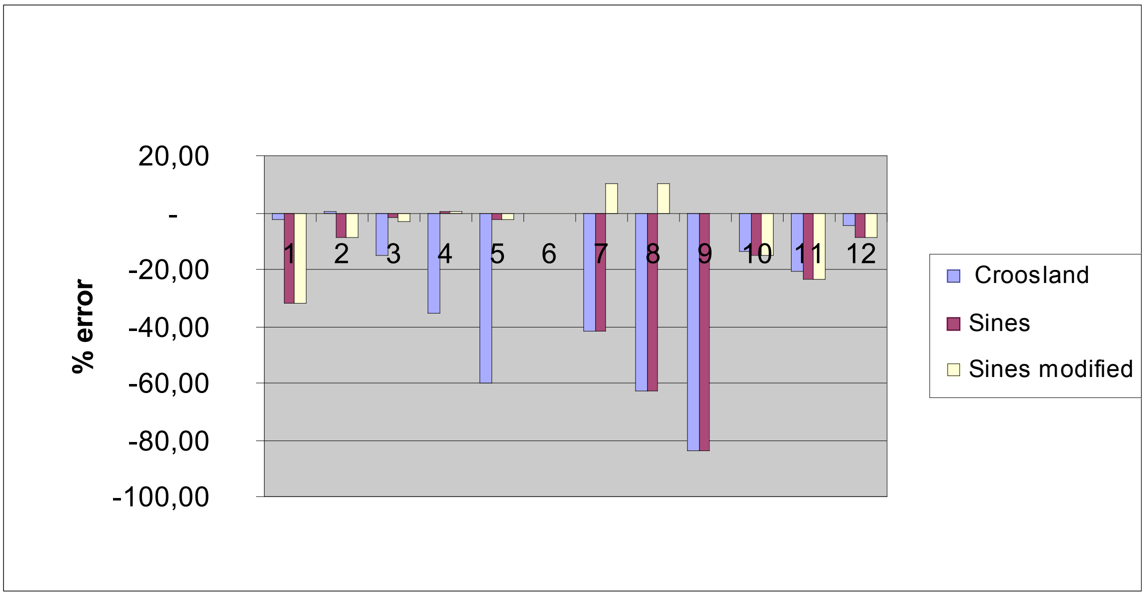

Figure 7 : Comparison between Sines, Crossland and Sines modified criterion
(experimental fatigue limit obtained by Luong's method)