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RESEARCH ARTICLE

EXPERIMENTAL STUDY OF THE INFLUENCE OF INCIDENTAL OVERLOADS ON THE FATIGUE BEHAVIOR OF SHEETS ASSEMBLED BY SPOT WELDS

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Abstract

The assembly of steel sheets using the spot-welding process is commonly used in the automotive industry - notably at Renault - for the production of the chassis. The stresses encountered in service due to rough roads or driving conditions are transmitted between assembled components via the welded points. Understanding their fatigue behavior under incidental overloads is therefore essential for ensuring their service life and permanently dimensioning the structure. In the present study, an experimental test campaign was conducted to analyze the fatigue failure modes of two identical steel plates joined by welded points and loaded in tension-shear. Two high-strength steel grades (HE360D and XE360D) and one mild steel grade for deep drawing (XES) were tested either at constant amplitude, or with incidental stresses occurring at a rate of one overload cycle for every 100 cycles applied. All cycles had a load ratio of 0.1 (undulating tension). The assembly of steel sheets using the spot-welding process is commonly used in the automotive industry - notably at Renault - for the production of the chassis. The stresses encountered in service due to rough roads or driving conditions are transmitted between assembled components via the welded points. Understanding their fatigue behavior under incidental overloads is therefore essential for ensuring their service life and permanently dimensioning the structure. In the present study, an experimental test campaign was conducted to analyze the fatigue failure modes of two identical steel plates joined by welded points and loaded in tension-shear. Two high-strength steel grades (HE360D and XE360D) and one mild steel grade for deep drawing (XES) were tested either at constant amplitude, or with incidental stresses occurring at a rate of one overload cycle for every 100 cycles applied. All cycles had a load ratio of 0,1 (undulating tension). The experimental results show that periodic overloading is beneficial to fatigue life in the case of high-strength steels, whereas the effect recorded is, on the contrary, a very marked collapse in fatigue properties in the case of mild steels.

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Introduction:-

During its use, a vehicle is subjected to different types of stress: normal, incidental (significant but occasional stress) and accidental (significant stress) (M. Pouranvariandal, 2001). It is therefore essential to know the behavior of materials, and more particularly of point-welded assemblies, for these different stresses both for the chassis parts and for the body.

The study of the resistance of welded assemblies under stresses of variable amplitude is crucial to guarantee the durability and safety of mechanical structures (K. Dand Van, 1993). The fatigue life of the welded points, particularly under tension-shear stresses, is influenced by various parameters, in particular the frequency and nature of the load cycles (F. Rossilon, 2008; B. Tikri, 2012). This article aims to examine the influence of incidental cycles, occurring at a rate of one cycle in a hundred, on the fatigue behavior of welded points loaded in tension-shear with a reference load ratio (RF) of 0, 1.

The main objective of this study is to quantify the impact of incident cycles on the fatigue life of welded points. More specifically, this research aims to:

1. **Measure the influence of an incidental cycle (at the rate of one cycle in 100) on the fatigue life of the welded points:** This analysis will focus on the progressive degradation of the resistance of the welds in the face of irregular load cycles, examining the frequency and severity of accumulated damage.
2. **Study the influence of the steel grade on fatigue resistance:** Different types of steel will be evaluated to determine how their metallurgical properties affect the fatigue resistance of welds. This part of the study will make it possible to identify the shades most resistant to incidental cycles.
3. **Analyze the effect of the thickness of the welded sheets on the fatigue life:** The geometry of the welded parts, in particular the thickness of the sheets, is a determining factor for the distribution of stresses and, consequently, for the lifespan tired. Samples with thicknesses of 1, 2 and 2, 5 mm will be tested to evaluate this variable.

Materials and Methodology:-

Materials:-

As part of the in-depth study of the fatigue of mechanical parts and the mechanics of fracture, a rigorous methodology will be developed to obtain the Force – Lifespan curves. These curves integrate incidental cycles and allow a relevant comparison with the reference curves obtained under constant amplitude loads. The test configuration was carefully determined to cover a wide spectrum of operating conditions. Several configurations are thus studied (B. Tikri, 2012):

- Three distinct steels: HE360D, XE360D and XES.
- Two different thicknesses: 2, 5 mm and 1, 2 mm.
- A coated steel, namely XES.
- An overload ratio, R, taking values of 1, 4 and 2, 3.

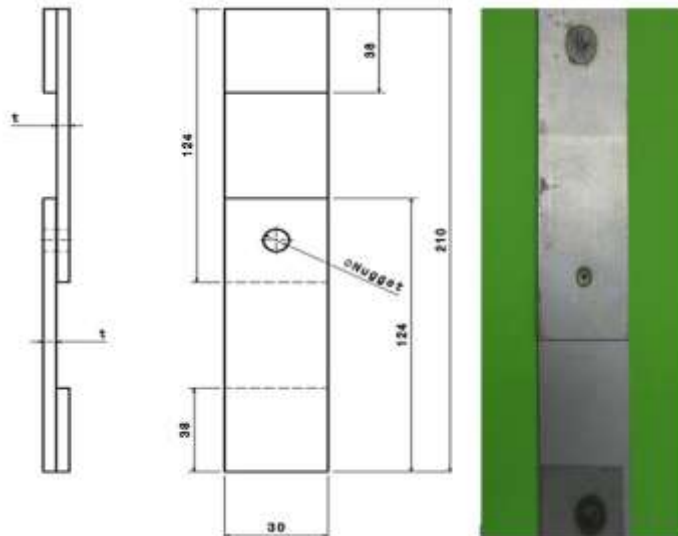


Fig. 1:- Geometry of the specimens (B. Tikri, 2012)

Table1:- Chemical composition and mechanical properties of steel grades (cross rolling direction).

Grade	C max	Mn max	S _i max	YS (MPa)	UTS (MPa)	Elongation(%)
XES360D	0.8	0.50	0.10	160-200	280-340	≥ 38
XE360D	0.8	0.70	0.04	340-400	420-490	≥ 23
HE360D	0.8	0.60	0.03	360-435	450-520	≥ 21

Methodology:-

Test conditions

The aim of the study is to evaluate the influence of periodical overloads on the fatigue behavior of spot welded automotive structures. The overload ratio representatives of in service car loading are used for that purpose. Two overload ratios are identified from subframe validation testing procedure and are equal to 1, 4 and 2, 3. Those ratios are obtained from the force amplitude of the excess cycle over the one of the constant amplitude loading. A test with periodical overloads corresponds to sequences with 99 constant amplitude cycles, followed by one overload cycle (figure 2).

The characteristics of the fatigue tests, carried out with an MTS fatigue machine with a capacity of ± 100 kN, are precisely defined. The frequency of the tests varies depending on the experimental conditions: 30 Hz for the reference tests without overload, and 20 Hz for the tests with overload. The description of the tests is divided into several methodical phases.

First, the fatigue characterization of the welded points is carried out under constant amplitude, with a load ratio (RF) equal to 0, 1. Second, an analogous characterization is carried out by introducing an incidental cycle every 100 cycles; this incident cycle is specifically defined by the established overload ratio.

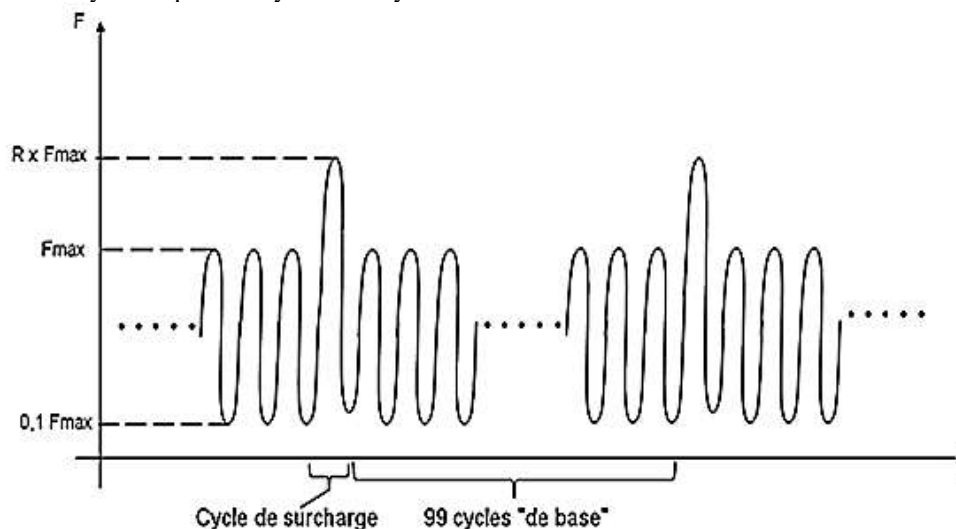


Fig. 2:- Description of the variable amplitude sequence with an overload cycle (here with ratio $R = 1, 4$) every 100 cycles (A. Berrehili, 2006; B. Tikri, 2007; H. Bidouard, 2009).

These tests make it possible to analyze the fatigue behavior of the welded points, by comparing performance under constant and variable load conditions. The methodological approach adopted, combining rigor and precision, aims to enrich the understanding of rupture mechanisms and to optimize the design of mechanical structures for increased durability.

The parameters of the HE360D, XE360D and XES360D materials will allow precise mapping of the fatigue behaviors of the materials under various loading scenarios. Their results will make it possible to determine the influence of the thickness of the sheets and the material on the fatigue life of point-welded assemblies. Comparison of the results obtained with those of constant amplitude loading provides crucial insights for optimizing the design of mechanical components subjected to variable loads in real industrial environments. This innovative and exhaustive methodology thus contributes to the advancement of knowledge in materials sciences and mechanical engineering.

In order to highlight the effect of incidents, three types of requests were chosen:

- Constant amplitude serving as a reference for other tests.
- Variable amplitude for an incidental/normal amplitude ratio (I/N) of 1, 3 at a frequency of one incidental cycle per hundred normal cycles.
- Variable amplitude for an incidental/normal amplitude ratio (I/N) of 1, 5 at a frequency of one incidental cycle per hundred normal cycles.

The tests will be carried out on welded assemblies stressed in tension-shear, with an RF load ratio of 0, 1. The methodology will include a series of fatigue tests where a more severe incident cycle will be introduced every 100 regular cycles. Regular and incidental cycles will be carefully monitored and documented to assess their cumulative effect on crack propagation and ultimate weld point failure.

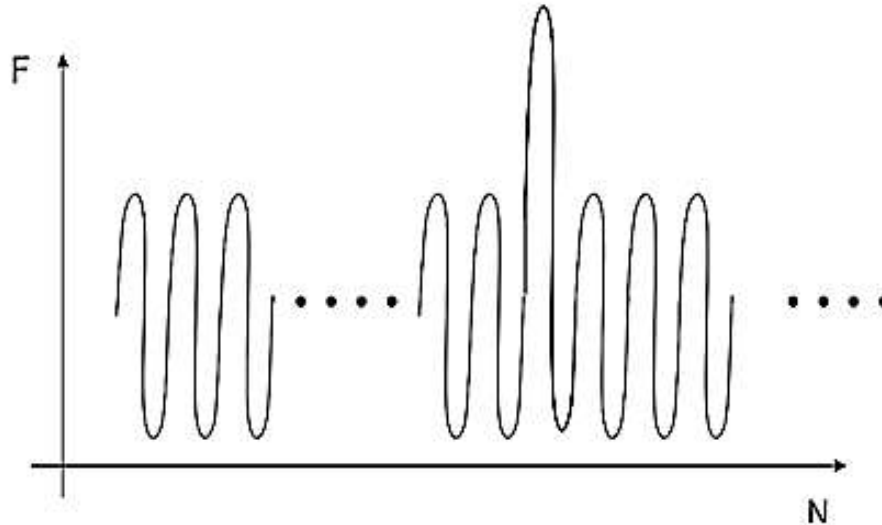


Fig.3:- Representation of the fatigue cycles applied to obtain the F-N curves with incidental overloads(H.D. Fant-Jaekels, 2001; F. Pennecandal, 2018).

This study, by deepening our understanding of the influence of incident cycles on the fatigue life of welded points, will provide valuable insights for the sizing and optimization of welded structures. The expected results will contribute to the development of recommendations to improve the durability of welds and to develop more effective preventive maintenance strategies.

In short, the integrated analysis of the effects of incident cycles, steel grade, and sheet thickness will significantly improve fatigue life predictions for welded assemblies, thus ensuring increased performance and enhanced security for critical industrial applications.

Results:-

On each specimen configuration, three types of tests were performed. A comparison of static tests with and without the anti-buckling system was carried out to characterize the static behaviour of the spot weld. Then fatigue tests with constant amplitude tensile shear loadings were performed in order to set up the force versus lifetime curves which are the reference in terms of fatigue strength. Fatigue tests results with overload allow to assess the influence of excess loadings on the spot weld fatigue strength.

Breaking modes

Two failure modes were observed after fatigue tests (fig.4). The first one is a shear failure of the nugget that is usually obtained for high force levels (a). For tests with overloads, load levels above which all the specimens experience this failure mode (so called transition level) is lower than tests with constant amplitude loading. The second one is a fatigue crack growth failure where the crack propagates first in the metal sheet thickness direction (b). Only tests leading to this failure mode were treated, as it corresponds to the failure mode that has to be prevented for car components.

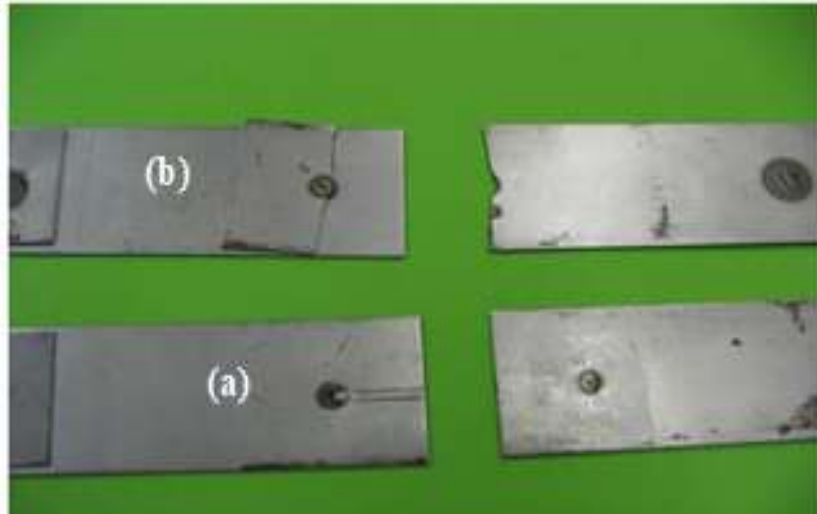


Fig. 4:- Specimens spot welded and broken according to two distinct modes of failure (a) by cracking of one of the two sheets, (b) by shearing of the core of the welded point.



(a) Shear failure of the nugget

(b) Propagating crack in the metal sheet

Fig. 5:- Facies of sections broken by fatigue (a) in the case of shear failure of the core, (b) for the case of cracking of the sheet metal.

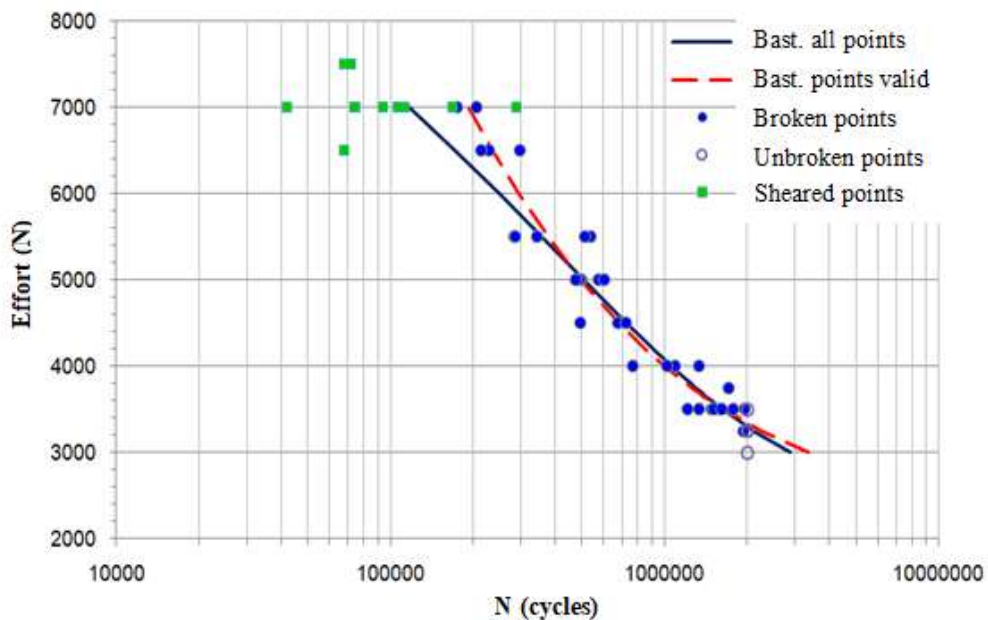


Fig. 6:- Preferred areas of the two modes of fatigue failure of spot-welded HE360D steel specimens according to the loading level.

❖ Two modes of failure of welded points by fatigue depending on the level of effort

a. Effect of incidental cycles on the fatigue life of welded points as a function of the overload ratio

❖ Case of steel grade HE360D

The fig.7 presents the three Basquin curves obtained for this material, the reference one (i.e. without overload) and the two curves with incidental overloads of ratios 1, 4 and 2, 3 respectively.

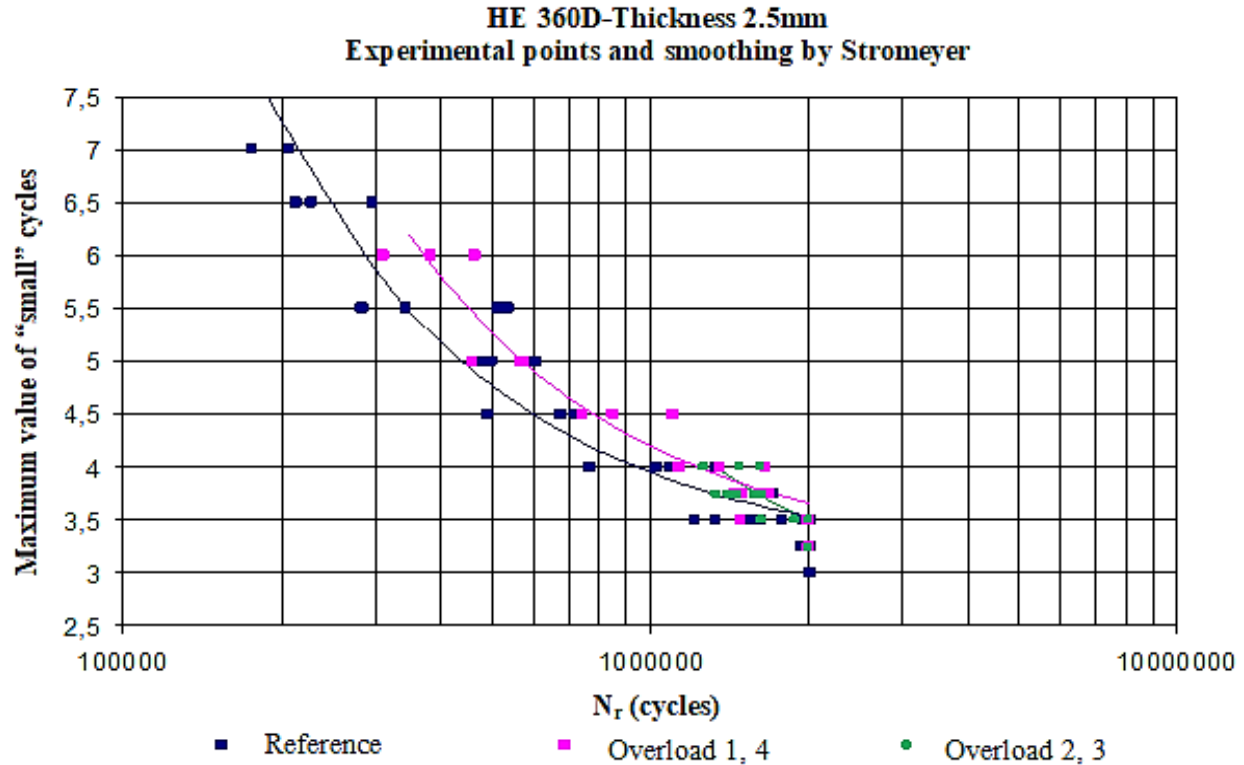


Fig.7:- Results of fatigue tests on HE360D steel specimens without overload cycles (reference), with overload cycles of ratio 1, 4, with overload cycles of ratio 2, 3.

The overload effect is significantly beneficial to the fatigue resistance of the welded points for this material. For a maximum force level between 3500 N and 6000 N, the relative gain in lifespan is of the order of 20%. The two overload ratios have approximately the same impact on the fatigue resistance of the welded points for service lives located at the origin (i.e. without overload) between $5 \cdot 10^5$ and $2 \cdot 10^6$ cycles. For the highest loading levels (and initial lifespans of less than $5 \cdot 10^5$ cycles), overloads with a ratio of 2, 3 are even more efficient in terms of lifespan gain than overloads with a ratio of 1, 4.

In summary, incidental overloads occurring at the frequency of one overload every 99 "base" cycles are beneficial to the fatigue resistance of the welded points for the HE360D material.

Case of steel grade XE360D

The fig.8 presents the three F-N curves obtained for this material without and with the two types of overloads considered for this study. As previously, the curves drawn are those corresponding to the Basquin model and were obtained with the ESOPE software from all the test results (except for the specimens broken by shearing of the welded point).

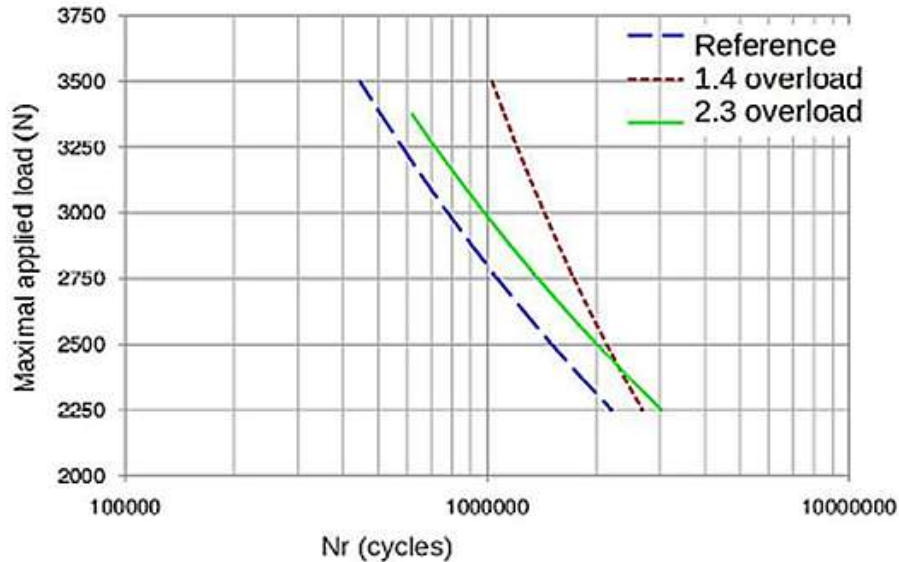


Fig.8:- Fatigue test results of XE360D steel specimens without overload cycles (reference), with overload cycles of ratio 1, 4, with overload cycles of ratio 2, 3.

As with the previous steel grade, XE360D steel shows a very clear improvement in fatigue resistance for both overload ratios tested. For initial lifespans of up to $2 \cdot 10^6$ cycles (obtained in the absence of overload, i.e. for constant amplitude loading), the insertion of periodic overloads of ratio 1, 4 or 2, 3 increase the life of the welded point. For the overload ratio equal to 2, 3, the relative increase in lifespan is of the order of 20% for any level of maximum effort while it is significantly more important and variable in the case of the ratio overload of 1, 4. This increase goes from 20% for the initial lifespan of $2 \cdot 10^6$ cycles, to more than 100% for an initial lifespan of $5 \cdot 10^5$ cycles.

It is for this material that the increase in fatigue resistance, linked to the occurrence of incidental overloads, is most marked.

Case of steel grade XES 360D

The fig.9 presents the superposition of the three F-N curves obtained for the XES steel without overload and with periodic overloads of ratio 1, 4 and 2, 3. The curves drawn correspond to the Basquin model; they were obtained using the ESOPE software by processing all the tests carried out except those for which the mode of failure was the shearing of the molten core of the welded point.

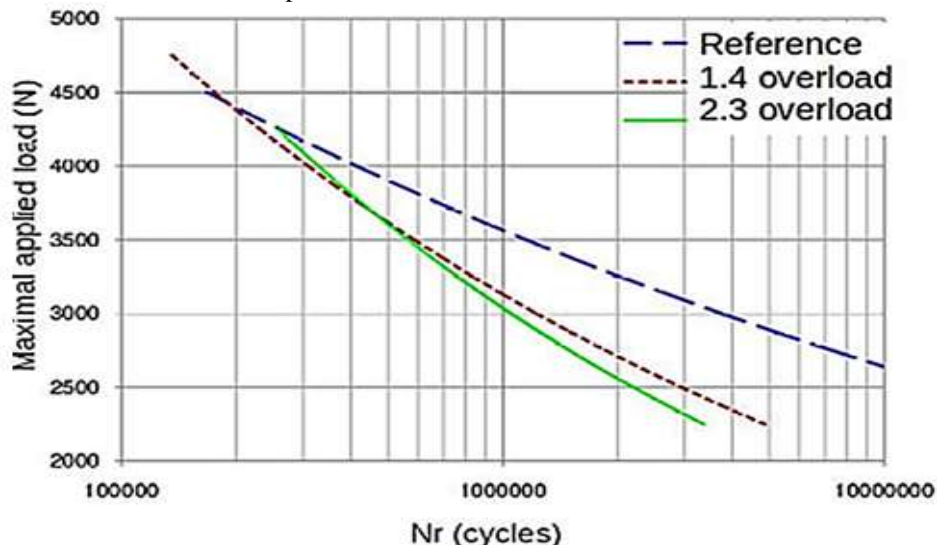


Fig.9:- Results of fatigue tests of XES steel specimens without overload cycles (reference), with overload cycles of ratio 1, 4; with overload cycles of ratio 2, 3.

For this material, the fatigue behavior in the presence of overload is the opposite of what was observed for the HE360D and XE360D steel grades: the insertion of incidental overloads in the constant amplitude traction-shear loading reduces considerably the lifespan of spot-welded specimens. This reduction in lifespan is all the greater as the maximum effort level of the basic cycle is low. It is a little more marked for the overload ratio equal to 2, 3 than for that equal to 1, 4. It is therefore particularly strong for the level of effort corresponding to the fatigue limit at 2.10^6 cycles (without overload), since this lifespan in the presence of overloads increases to approximately 800,000 cycles (the reduction ratio of the lifespan is thus equal to 2, 5 for this level of effort).

Analysis of Results:-

The explanations of the results obtained during this study highlight several crucial phenomena. First of all, it was observed that a significant overload causes a break in the joint plane earlier, thus reducing the lifespan of the components analyzed. However, the work hardening induced by this overload plays a beneficial role in improving the fatigue resistance of materials. This work hardening effectively delays the propagation of the crack, thus contributing to greater durability of mechanical structures.

The overload effect is significantly beneficial to the fatigue resistance of the welded points for this material. For a maximum force level between 3500 N and 6000 N, the relative gain in lifespan is of the order of 20%. The two overload ratios have approximately the same impact on the fatigue resistance of the welded points for service lives located at the origin (i.e. without overload) between 5.10^5 and 2.10^6 cycles. For the highest loading levels (and initial lifespans of less than 5.10^5 cycles), overloads with a ratio of 2, 3 are even more efficient in terms of lifespan gain than overloads with a ratio of 1.4.

In summary, incidental overloads occurring at the frequency of one overload every 99 "base" cycles are beneficial to the fatigue resistance of the welded points for the HE360D material.

Example for the tests at 3500 N: there is mainly no rupture of the specimens at 2.10^6 cycles for the overload ratio of 1, 4 (only 1 specimen broken out of 5) while the rupture is almost systematic before 2.10^6 cycles for the reference curve (8 broken test pieces out of 9).

Furthermore, the results show that there is a competition between two failure modes. On the one hand, the core of the welded point is subjected to shear stresses. On the other hand, the sheets, particularly near the bottom of the notch, undergo tensile forces accompanied by a high concentration of stress. This duality of failure modes complicates the analysis and prediction of the fatigue behavior of welded points, requiring a combined approach for an exhaustive understanding and precise modeling of these phenomena. The results obtained provide valuable insights for improving design and welding practices, aimed at minimizing the risks of premature failure under varied service conditions.

Conclusion:-

Two forces – lifespan curves were established for each of the three grades of steel studied based on the experimental results of fatigue traction-shear tests on spot-welded specimens fitted with a stiffener. The first of these three F-N curves corresponds to constant amplitude loads (so-called reference curve), the other two curves are the results of variable amplitude tests including an incidental overload cycle, with ratios 1, 4 and 2, 3 respectively, every 99 "basic" cycles. These last two loadings in fact correspond to the periodic insertion of a well-defined overload cycle within a constant amplitude load. In this way, the influence of these overloads is easily quantifiable from the point of view of the fatigue resistance of the welded point. For the entire experimental campaign, all applied force cycles (basic cycles and overload cycles) have a load ratio equal to 0,1.

The superposition of the three F-N curves obtained for each grade of steel very clearly reveals the influences of overloads on the fatigue behavior of the welded points.

For the two steel grades HE360D and XE360D, the appearance of incidental overloads is beneficial to the fatigue life of the welded point since it increases its lifespan for identical basic cycles. For the third material tested (XES steel grade), the effect is very clearly the opposite since there, on the contrary, the overload cycles lead to a very significant reduction in the lifespan compared to what it is when only the basic cycles are applied to the

specimens. cette différence peut être due à la présence des contraintes résiduelles introduites lors de soudage. This difference may be due to the presence of residual stresses introduced during welding (D. Wel-Doret and al, 2023).

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