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Investigations on the influence of cold-forming and associated residual stresses on the fatigue strength of thin-walled details

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Abstract

A code for the design of cold-formed thin-walled structures in accordance with fatigue requirements currently does not exist in Europe. Part 1993-1-3 of the Eurocode [1] only standardizes the static design. In part 1993-1-9 [2] for design and construction under fatigue loads cold-formed thin-walled profiles are explicitly excluded. Corresponding elements have, however, become established in the construction of racking systems, as they represent an efficient and economical way of creating storage capacities. In contrast to the former use of storage systems, manual retrieval and storage (S/R), increasing automation through S/R-machines leads to cyclical loads in uprights and struts. In addition to purely static loads, this results in a dynamic component that cannot be neglected.

Experimental investigations, such as monotonic and cyclic tensile tests, are used to determine changes in material properties after cold-forming by bending. Special focus is put on the influence of bending radii in combination with the thickness on the plastic deformation and associated internal residual stresses. These parameters can have a significant impact on the fatigue behavior. The aim of the tests with a new invented testing device is to provide a basis for the development of adequate fatigue design rules for storage systems.

Keywords

Fatigue strength, cold-forming, residual stresses, resonance testing

1 Introduction

Cold-formed members in construction are currently designed according to EN 1993-1-3 [1]. The rules provided by this code, however, do not include any design rules for fatigue. Whereas, EN 1993-1-9 [2], which provides rules for the fatigue resistance of steel structures, contains no details applicable to thin walled cold-formed members. For some fields of application, however, the consideration of fatigue loads and the determination of fatigue resistance is a crucial part of safety verification. Automated storage racks belong to this application group, where frequent and repeated operational loads led to fatigue damages in cold-formed profiles. Based on this experience and the urgent demand for harmonized and reliable fatigue design rules for cold-formed members, an European research project, FASTCOLD, was initiated. This project aims at the determination of fundamental parameters influencing the fatigue resistance of cold-formed members and at the development of functions and dependencies allowing for the formulation of fatigue resistance functions and design rules. Main part of the project are experimental investigations.

The subject of the investigations are cold-formed members produced from cold-rolled steel sheets. The cold-forming process is one of the key parameters to be considered in the planning and the evaluation of the tests. In more detail, the following cold-forming aspects were considered so far:

– Hot or cold-rolling process of sheets
– Roll-forming process of members
– Press-braking process of members

Each of these aspects needs to be analysed and extended in detail, e.g. the thickness of the sheets and the bend radius. The variation of the properties of cold-formed members needs then to be combined with possible loading effects, where in particular the orientation of stresses in relation to strains caused by the cold-forming process is of concern. Therefor a testing matrix was developed covering representative combinations of cold-forming effects and loading scenarios. Including variations of stress level and repetitions required for the provision of a statistic data base a total of 600 fatigue tests was estimated. Taking into account the expected average number of cycles $N = 2{\cdot}10^6$ per specimen (high cycle fatigue) it led to an expected total number of more than 10^9 cycles. Considering this very high number it was necessary to develop a high frequent testing method allowing for the achievement of the required results within the project duration.

The general concept for the identification of the main influencing parameters comprised the following steps:

- Mechanical and fatigue properties of the virgin material
- Mechanical and fatigue properties of the virgin material after additional stretching
- Fatigue properties of cold-formed details with varying R/t-ratio and different cold-forming process

2 Properties of the Virgin Material

The two materials used in the research project correspond to the steel grades S355MC and S460MC. These are steel grades thermomechanically rolled during production, which have special properties with regard to cold-forming processes. In order to assess the material properties in the initial state, sheet samples with a thickness of 3.5 mm were subjected to tensile tests. The tensile specimens of the base material were prepared in two perpendicular orientations. On the one hand, samples were produced parallel to the production direction of the initial sheets and on the other hand, samples were produced crosswise. The specimens transverse to the direction of rolling are of particular importance, as this corresponds to the expected direction of elongation during cold-forming, for example in the roll-forming process. The resulting technical stress-strain curves from the tensile tests on the virgin materials are shown in figure 1 below.

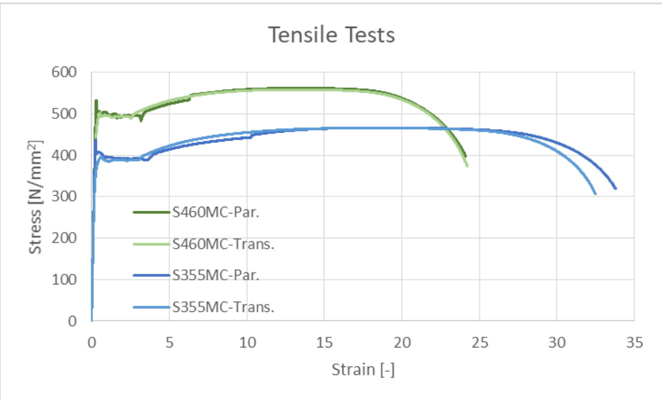

Figure 1 Technical stress strain curves of investigated virgin materials

The stress-strain curves obtained for the both steel grades do not exhibit a significant dependency on the direction of loading in relation to the rolling direction. The elastic stiffness in each tests was very similar and can be represented by the Young's modulus E = 210 000 N/mm^2.

Both materials, however, have a yield strength above the nominal value, depending on the steel grade and the orientation of loading. Also the strain hardening and the maximum elongation depend on the steel grade, but not on the direction of loading.

The material S355MC has a lower yield strength of 385 N/mm^2 and an ultimate tensile strength of about 465 N/mm^2 for both sample orientations. The elongation at the fracture point is between 30 and 35 %. The upper yield strength varies depending on the sample orientation. According to the results, the upper yield strength for the manufacturing direction is 440 N/mm^2. Orthogonally to the manufacturing direction, thus parallel to the expected direction of elongation during cold-forming in the roll-forming process, the upper yield strength is 400 N/mm^2. The range between the upper and lower yield strength is correspondingly higher parallel to the manufacturing direction than transversely to it.

The material parameters of the examined steel S460MC behave similar. The lower yield strength is 480 N/mm^2 and the ultimate tensile strength reaches values of more than 550 N/mm^2. The elongation at fracture point is comparatively lower at less than 25 %, but fulfils the standard requirements. The upper yield strength varies again with the orientation of the test specimens in relation to the direction of manufacturing of the initial sheets. The observations made in the tensile tests confirm the experience made by the producers which is that the greater the angle between the orientation of the test specimens and the direction of manufacture, the greater the value of the upper yield strength and thus the range between upper and lower yield strength.

3 Concept for Fatigue Tests

At the Institute of Steel Construction of RWTH Aachen, a new testing device has been developed and built for the research project to determine the fatigue strength of cold-formed thin-walled sheets. In the following, the structure and the operating principle of the testing device will be explained in order to make the interpretation of the test results understandable.

3.1 Testing Device for Fatigue Tests

The developed testing device uses the functional principle of the resonance of single-mass oscillators. A horizontally moving mass is brought into oscillation under a harmonic excitation force. The stiffness of the oscillator results from the stiffness of the test specimen together with additional variable springs. By varying the spring stiffness and the excitation the dynamic system can be adjusted such, that the desired load amplitude is achieved in a resonance situation. A photo of the testing device is shown in figure 2.

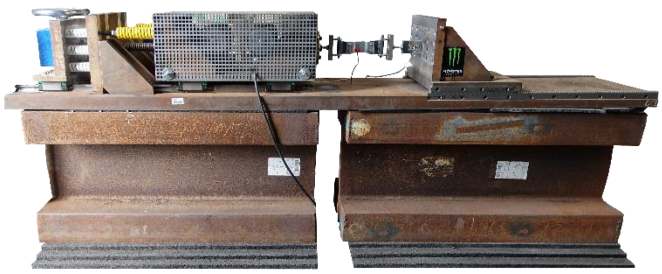

Figure 2 Photo of testing device

The testing device, mounted on two steel slabs, contains a horizontally movable carriage. Two unbalance exciters are mounted on this carriage, providing horizontal excitation with adjustable frequency and force amplitude. The rotational movement of the two exciters is opposite, resulting in a superposition of the centrifugal forces along the length of the testing device and a resolution of the centrifugal forces in the vertical direction. The carriage accordingly represents a dynamic system with one degree of freedom.

On the left side of the carriage are individual springs which, depending on the configuration, can be arranged in a parallel or a serial arrangement. The test specimens are clamped to the right of the carriage for the tests. In combination with the clamping elements, these elements also represent a serial connection of springs. The combination of all springs results in an overall spring stiffness with a substantial influence on the system behaviour, as the following schematic (figure 3) illustrates.

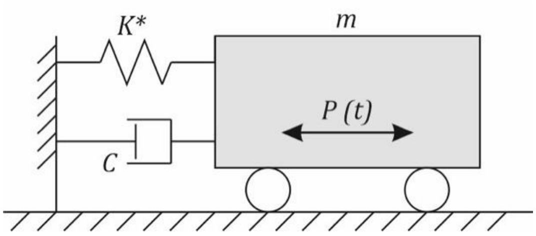

Figure 3 Schematic representation of the testing device, damped single mass vibration system under harmonic excitation [3]

The damping C shown in the sketch mainly corresponds to the friction of the carriage in the adjusted rail system in which all oscillating elements are fixed. While the friction in the rail system can only be determined experimentally, the total spring stiffness of the system can be calculated and modified. The total stiffness of a parallel connection results from the cumulative stiffness of all individual springs:

$$K^* = \sum_{i=1}^{n} K \qquad (1)$$

If springs are connected in series, the total stiffness of the connection is to be calculated as follows:

$$\frac{1}{K^*} = \sum_{1=1}^{n} \frac{1}{K} \qquad (2)$$

The reciprocal of the total spring stiffness can therefore be calculated from the sum of all reciprocal values of the individual springs. Using the two formulae (1) and (2) above, the total spring stiffness K^* of all springs utilised in the testing device can be calculated accordingly. This stiffness can then be used to determine the eigenfrequency ω of the carriage in the testing device:

$$\omega = \sqrt{\frac{K^*}{m}} \qquad (3)$$

The eigenfrequency ω of the system is only dependent on the mass m of all oscillating components and the total spring stiffness K^*. If the eigenfrequency ω of the system, which can be influenced by the spring configuration, and the excitation frequency Ω of the unbalance exciters converge, the system is in resonance and lead to large oscillating amplitudes. These amplitudes can be regulated by damping and thus, by the friction in the rails of the system.

Depending on the frequency ratio n between excitation frequency Ω and eigenfrequency ω, the magnification factor V resulting from the dynamic system behaviour can be determined. This factor represents the ratio between the statically acting centrifugal force P_0 of the unbalance exciters and the dynamically acting resonance forces in the system [3].

$$V = \frac{1}{\sqrt{(1-n^2)^2 + (2 \cdot \zeta \cdot n)^2}} \qquad (4)$$

With: $n = \frac{\Omega}{\omega}$

$\zeta = \frac{C}{2 \cdot m \cdot \omega}$

For the excitation frequency of the unbalance exciters equal to the eigenfrequency, the frequency ratio n corresponds to the value 1 and the divisor of the formula (4) for the magnification factor is equal to the squaring of the damping degree ζ multiplied by two. If the friction of the rail system is very low, the damping becomes very low. As a result, the magnification factor according to formula (4) can reach very high values. The resonance effect now has its maximum influence on the behaviour of the testing device. Compared to the static centrifugal force of the unbalance exciter, the dynamic system forces are a several times higher.

Besides the advantage of a high possible testing frequency, which results in a significant time advantage, the whole system can be preloaded. Thus the test specimens can be permanently cyclically loaded under tensile forces. The preload in the system has no relevant influence on the resonance behaviour.

To illustrate the magnitude of the resonance effect in the testing device, the resonance spectrum for test parameters set during some of the experiments is presented subsequently. The mass of all vibrating components m is about 250 kg. The arrangement of all springs including the spring effect of a test specimen results in a total spring stiffness K^* for this example of 17 000 N/mm. The parameters result in an eigenfrequency of about 41 Hz at which resonance is achieved, as the following figure 4 indicates.

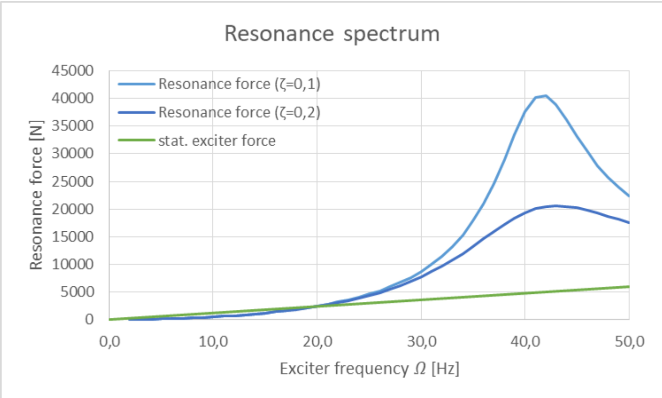

Figure 4 Resonance spectrum for the testing device under defined experimental parameters

The linear correlation between centrifugal force and the frequency of the unbalance exciter is shown in green. At a maximum possible exciter frequency of 50 Hz, the two unbalance exciters generate a total static exciter force of 5 944 N. In addition to the statically assumed combined centrifugal force of the two unbalance exciters, the resonance force generated in the dynamic system is shown. The maximum value of the ordinate can be seen for a value of the abscissa in the range of the eigenfrequency, independent of the damping degree.

For a damping degree of ζ = 0.1, a resonance force of 40 kN can be achieved at a frequency of the unbalance exciter of 41 Hz. However, the static force introduced into the system is approximately 5 kN. This corresponds to an increase by a factor of eight. If the friction in the system increases, the degree of damping also increases, reducing the dynamic force due to resonance. This is also shown in figure 4 by the function of the resonance force for ζ = 0.2 in this case. The force acting in the system can only be increased by a factor of four. The reduction of friction in the system is therefore essential for the operation of the testing device.

Depending on the configuration of all relevant parameters, even small changes can have an effect on the system behaviour. This susceptibility to small changes leads to a difficult evaluation of the tests. For clarification, the evaluation is explained in the following using a selected example.

3.2 Methodology for Evaluation of Fatigue Tests

The selected example represents the test results on a waisted flat tensile specimen of material S355. The specimen has a thickness of 3.5 mm and at the tapered point a width of 10 mm. The expected fracture point of the specimen therefore has a cross-sectional area of 35 mm^2. Only the upper force F_max and lower force F_min, resulting from the load changes, were recorded. The results are shown in the following figure 5.

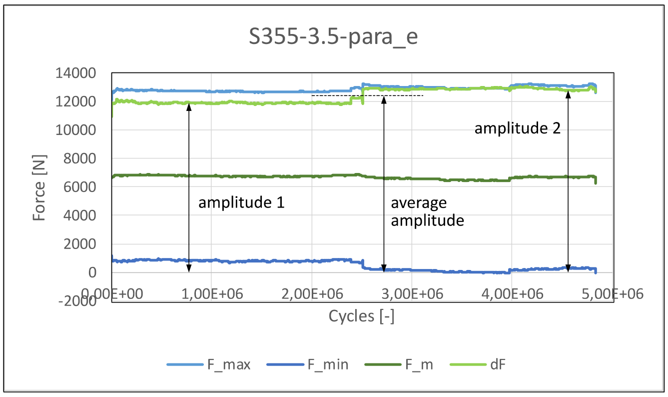

Figure 5 Loading history of flat tensile specimen S355-3.5-para-e

The mean force F_m from the mean value and the force amplitude dF from the difference between the recorded forces were then calculated from the displayed upper and lower force for each cycle. In total, the test specimen was subjected to $4.84 \cdot 10^6$ load cycles until failure occurred. The figure also illustrates that it is practically not possible to keep the load amplitude constant during a test. As visible the force amplitude varies over the duration of the test. The figure shows that at the beginning of the test, a cyclical stress change corresponds approximately to the indicated amplitude 1. In the second half of the test, a comparatively larger amplitude 2 is acting. In order to enable the evaluation of the fatigue loads, an average stress amplitude must be determined for the entire test. The fundamental principle for this is shown in Figure 6.

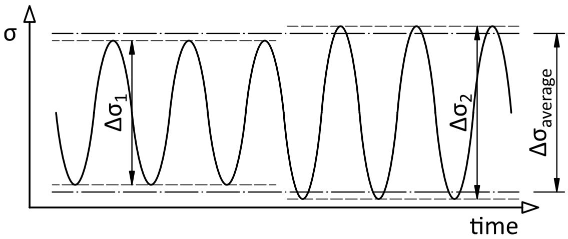

Figure 6 Explanation of the average stress amplitude

To determine an average amplitude (fig. 5), all recorded cycles are divided into load classes of 350 N and converted into stress classes. The stress classes have a resolution of $\Delta\sigma = 10 N/mm^2$. The time-force amplitude records (fig. 5) result in the stress classes shown in figure 7.

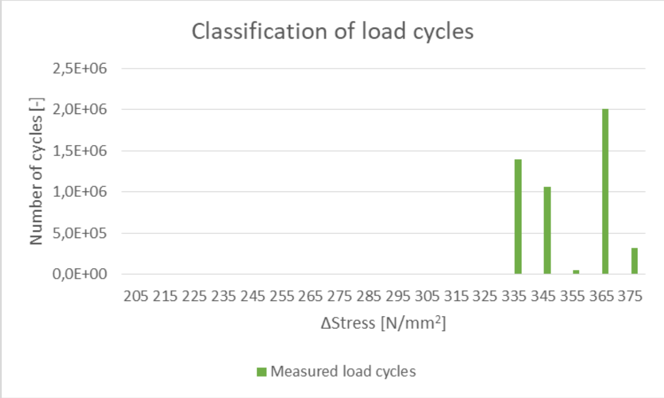

Figure 7 Load classes of flat tensile specimen S355-3.5-para-e

All measured load variations were with a stress amplitude between 320 and 380 N/mm^2. The most frequently recorded stress class with stress amplitudes between 360 and 370 N/mm^2 counts about $2 \cdot 10^6$ load cycles. In average, a stress amplitude of 352 N/mm^2 was introduced into the test specimen in this test. To determine the fatigue relevant load cycles, the measured number of load cycles cannot directly be summarized. The load cycles of all stress classes are first converted to a damage equivalent amplitude using the Miner Rule according to the linear damage accumulation. The general Miner Rule is as follows:

$$N_{ref} = \Sigma_{classes} \cdot \left[N_{class} \cdot \left(\frac{\Delta\sigma_{class}}{\Delta\sigma_{ref}} \right)^m \right] \tag{5}$$

For the conversion of the number of load cycles using the Miner rule, the exponent m of the equation is required. This exponent is not known for cold-formed details. However, since the scattering of the stress classes is rather limited, the influence of m is not large. In the presented test results, the load amplitude were converted with the assumed exponent $m = 3$. This corresponds to the slope of an S-N curve for a detail category 160 according to Eurocode 3 [2], thus flat steels or plates with sharp edges. After conversion of the number of load cycles to the average stress amplitude of $\Delta\sigma_{ref} = 352 N/mm^2$ as reference, the diagram can be adjusted as follows:

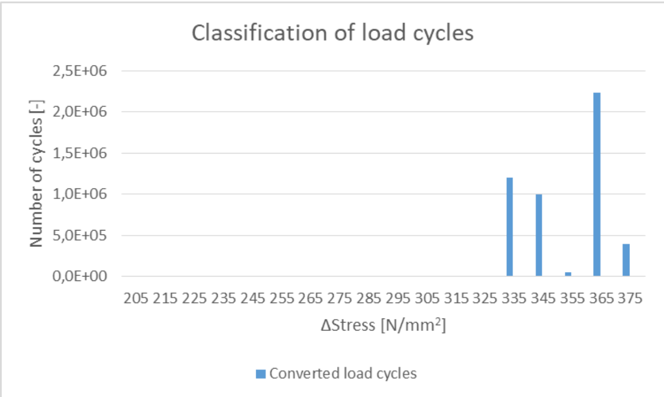

Figure 8 converted load classes of flat tensile specimen S355-3.5-para_e

The number of load cycles in the stress classes above the average stress amplitude has increased. In relation to the reference level, these load changes have now a correspondingly higher influence on the failure of the test specimen. In contrast to this development, the number of load cycles in the stress classes below the reference level has decreased. The influence of these stress classes on fatigue failure is reduced. Referring to a stress amplitude of 352 N/mm^2 the fatigue crack occurred after about $4.88 \cdot 10^6$ load cycles.

If the average stress amplitude and the corresponding number of load cycles are determined for several specimens of a standardized type, a fatigue strength curve for direct stress ranges can be generated based on these values. The fatigue strength of the test specimens can thus be determined.

4 Fatigue Test Results

4.1 Virgin Material

The fatigue resistance of the initial materials was tested on waisted flat tensile specimens. All specimens had a thickness of 3.5 mm and a cross-sectional area of 35 mm^2 at the weakest point, as shown in figure 9. All specimens were cut out of the sheets by water jet cutting in order to prevent changes of the material properties in the cutting area.

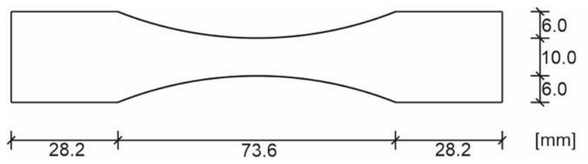

Figure 9 Geometry of flat tensile specimens

To evaluate the results of the fatigue tests for the mentioned materials, the number of load cycles in combination with the average stress amplitude were plotted in the following S-N diagram. In addition to the test results, the fatigue strength curve according to Eurocode 3 Part 1-9 [2] is also plotted for a detail category 160 (Plates and flats with sharp edges). This should facilitate the interpretation of the results. The horizontal areas of the fatigue curve shown correspond to the nominal yield strength of materials S355 and S460. The slope of the curve corresponds to the value 3 and is therefore equal to the assumed exponent m in the Miner Rule (equation 5).

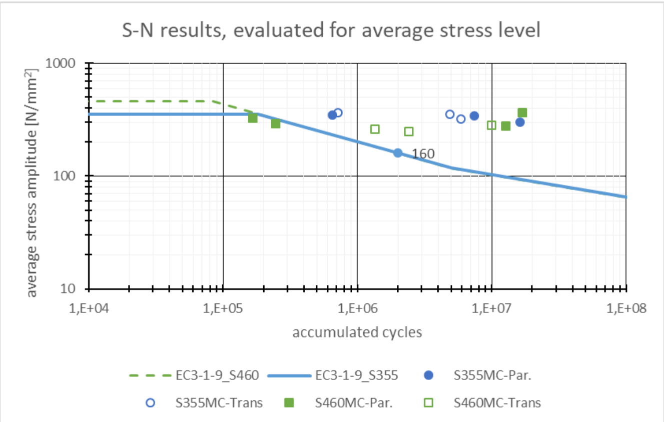

Figure 10 Results of fatigue tests on flat tensile specimens

Most of the results are above the curve representing detail category 160 according to Eurocode 3, except two of the fatigue tests. These are below the fatigue strength curve with a relatively low number of load cycles. The two specimens show the same orientation to the initial plate (parallel to the manufacturing direction). Despite the fact that the nominal yield strength of the material was not exceeded, only a relatively small number of load cycles could be achieved. In contrast to this comparatively low fatigue resistance, two further specimens with the same material properties and orientations were tested with a high number of load cycles. One of the specimens was tested with an average stress amplitude of 366 N/mm^2. The test was stopped after 16.8·10^6 load cycles and showed no fatigue characteristics despite the high load. The scatter of results for these material properties associated with mentioned specimen orientation is correspondingly significantly high. In average, the fatigue strength of these specimens is above the fatigue strength curve for a detail category 160.

All samples were tested with high average stress amplitudes above 250 N/mm^2. In principle, it can be determined on the basis of the tests performed that the orientation of the specimens has no influence on the average fatigue strength. Only the scattering of the test results is higher in case of specimens oriented parallel to the direction of manufacturing. Overall, high fatigue strengths can be determined from the results.

4.2 Profiled Specimens

The results of cold-formed test specimens shown here were all produced by roll-forming process from sheets with the steel grade S355MC. Although the results do not represent the totality of all the results obtained with the testing device, they provide the first basis for all materials and types tested. The geometry of all test specimens basically correspond to the illustration in figure 11, but the specimens differ in terms of material thickness t and bending radius R. Contrary to the tests on the flat tensile specimens, in which the load cycles were determined from the introduced force, the stress cycles in the profiled specimens were registered and recorded by strain gauges. The position of the gauges was always the same. The stress is subsequently determined by means of the Young's modulus of the virgin material determined in chapter 2.

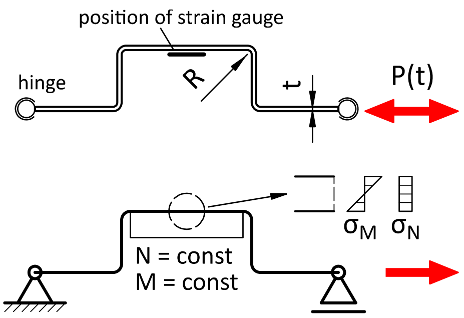

Figure 11 Geometry of profiled specimens (simplified)

The specimens have nominal thicknesses t between 1.5 and 3.5 mm. Due to cold-forming, the thickness may vary slightly in the areas of the bend. The bending radii R of the test specimens used for cold-forming vary between 1.5 and 4 mm. However, the relevant factors for the evaluation of the fatigue tests are not the individual parameters of the test specimens but the ratio R/t between bending radius and material thickness. In order to enable a classification of the test results, the results of the different specimen geometries are directly represented by the R/t ratio in figure 11. In addition, a fatigue strength curve according to Eurocode 3 Parts 1-9 is again shown for a detail category 160. This only serves to facilitate the classification of the results.

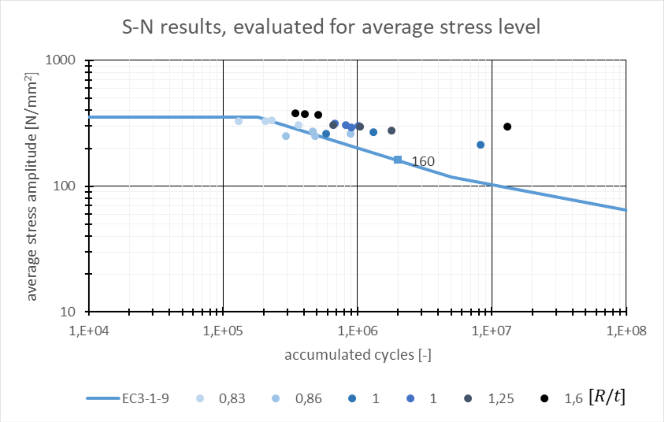

Figure 12 Results of fatigue tests on profiled specimens (all S355MC), labelled according to R/t

For all specimens the fatigue cracks were located in the bending areas oriented towards the centre of the specimens. However, the stress amplitudes corresponding to the fatigue loads could not be determined at the related location. It was not possible to apply the strain gauges in the bending radii, so they had to be placed in the middle of the specimens. In the future, the increase in stress in the bending area compared to the position of the strain gauges must still be carried out using finite element calculations. The current determination of the stress amplitudes therefor represents a conservative evaluation of the test results.

The stress amplitudes in the central area of the test specimens are all in the order of magnitude of the nominal yield strength. It is noticeable that the R/t ratio has a significant influence on the fatigue strength. The larger the ratio, the more load cycles can be absorbed by the specimen respectively higher stress amplitudes can be achieved with the same number of load cycles. From a R/t ratio ≥1 all the specimens can be assigned to a fatigue strength curve of a detail category 160. Even the specimens with a lower R/t ratio have a high fatigue resistance and could be assigned for example to a detail category 125 according to the results.

For the determination of the gradient of a fatigue strength curve the results are not yet sufficient in their number. Also the evaluation of the remaining stresses caused by bending cannot yet be fulfilled, as some tests are still pending.

An assessment of the slope of the strength curve and the remaining stresses caused by bending in the component will be based on a larger number of tests in the remaining period of the research project. However, the fatigue strength of cold-formed elements can already be rated as high in relation to detail categories from Eurocode 3 Parts 1-9.

5 Conclusion

By means of the developed resonance testing device, a large number of fatigue tests have already been carried out. The experiments on the virgin material can already show a high fatigue resistance of thin walled sheets. The profiled sheets manufactured from the raw material were also subjected to cyclical loads. These test specimens demonstrate a high resistance to oscillating loads as well. Despite a conservative assessment, detail categories can be formulated on the ratio of bending radius to material thickness. If the ratio R/t is above a value of 1, the results show that the profiled specimens can be assigned to the highest detail category 160 of the Eurocode 3 Part 1-9.

References

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