Full paper

Fatigue Design Of Cold-Formed Thin-Walled Z-Rails Subjected To Concentrated Load

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Abstract

Cold-formed thin-walled steel members are extensively used in rack storage structures due to their advantageous geometrical and mechanical properties for a minimum weight. In automatic multi-deep rack systems, shuttles are used to bring pallets to their final storage position; these shuttles are usually circulating on elements made of Z sections, which facilitates their movements and ensuring a sufficient bearing and stiffness capacity. Due to the multiple passages of the shuttles, fatigue problems could occurred on these profiles, but this issue is not fully covered by the existing European normative document EN1993-1-9. This paper presents part of the results of a large experimental fatigue test campaign, in which 34 members made of thin-walled cold formed steel Z sections have been tested, in order to characterize the fatigue resistance of two details as a part of the Z-rail. The main objective of these tests was to derive the S-N curve associated to both studied details. As a result, design provisions to assess the fatigue resistance of Z-rails subjected to fatigue load are proposed for the practitioners, referring to the recommendations of prEN1993-1-9.

Keywords

Thin-walled members, Z-shape section, Rack structures, Fatigue, S-N curve, Cold-formed section, EN1993-1-9, Experimental campaign

1 Introduction

In the competitive self-supporting storage rack structures market, there is a growing need to optimize the structural solutions and maximize the storage capacity within a minimum given area. The utilization of cold-formed sections is a promising solution, particularly in multi-deep systems that can accommodate multiple pallets over an extended length. This system generally implies the use of an automatic shuttle circulating on elements which carry the pallets, and, due to the multiple passages, the members are subjected to several stress variations in a limited time. Consequently, a fatigue failure may be observed after a certain number of cycles.

Nowadays, fatigue phenomenon has been the topic of extensive research, with a particular emphasis on the characterization of the fatigue resistance of structural details [1] that have not yet been addressed by the relevant code, EN1993-1-9 [2]. Although this normative document contains provisions for the design of structural details against fatigue, only a limited list of details is proposed in its current version, such as elements with welded parts, orthotropic desks and runway support beams.

Even if the forthcoming version, prEN1993-1-9 [3], extends the number of the characterised details and proposes new modified S-N curves, a number of details that can be encountered in steel buildings need to be further investigated. Additionally, there is no clear indications for the application of these rules to details made of cold-formed elements. Regarding the fatigue behaviour of structural details made of cold-formed steel members for racking structures, no recommendation is given in the reference normative document EN15512 [4].

In addition to the research conducted on hot-rolled profile made of high strength steel [5], several investigations have been also performed on cold-formed elements. Souto et al. [6] presents the results of an experimental fatigue test campaign performed on Z-shaped section members in the framework of the RFCS European project FASTCOLD

[7]. During this project, analytical, numerical and experimental investigations have been performed with the objective of deriving the S-N curve for the detail for a specific section at mid-span with a support that restrained vertical displacements on the web.

Within the present paper, the results of the investigations conducted on the fatigue resistance behaviour of Z-rail members used in multi-deep rack storage structures, subjected to the load of the shuttle that circulates on their lower flanges, are presented. To reach this objective, an experimental campaign including 34 fatigue tests on two specific details was carried out by applying different constant load variations on the lower flange of the Z-section rail. Among these 34 tests, 18 were performed to study the detail at mid-span (first structural detail, named as *MSXX*) and 16 to investigate the fatigue resistance of the support detail. In addition, for each setup configuration, static tests have been realised. As an outcome of this experimental campaign, an S-N curve was derived following the philosophy of prEN1993-1-9. In the following, only the first type of fatigue tests is detailly addressed (i.e. the mid-span test configuration). All the details about this experimental campaign can be found in [8].

This research is part of a Walloon region project, called ACTIONS (convention N° 8528), involving the industrial partners STOW and GDTech, the private research company CRM group and the University of Liège.

2 Description of the experimental campaign

2.1 Tested specimens and characterisation of the material

The experimental campaign was performed using for all the tests a unique profile made of cold-formed rolling HX420LAD steel grade; the geometrical properties are illustrated in Figure 1(a). The ratio between the internal radius and the thickness is equal to 1.23. This section has been identified as one of the most frequently used sections by the industrial partners of the aforementioned project amongst a wide range of available profiles on the market, with heights varying between 160 and 220 mm and thickness between 2.5 and 3.5 mm. The 34 fatigue tests have been performed in two sets, aiming at characterizing two distinct details.

Tensile coupon tests have been performed in order to define the actual material properties. As specified in ISO377 [8], the mechanical properties of the material exhibit variation according to the orientation of the extracted coupon specimens, caused to the roll forming technique that involves coiling and uncoiling processes. By consequence, three dog-bone specimens have been extracted: (i) perpendicular to the longitudinal direction on the web (named *AV*) (ii) longitudinally on the web (named *AH*), and (iii) longitudinally in the larger flange (named *S*); the orientations are schematized in Figure 1(b). Those tensile tests have been performed twice.

Tests results are provided in Figure 2 and Table 1 gives the main mechanical properties. Compared both orientations, it could be clearly seen that as expected, the properties are note the same, as the longitudinal properties are smaller than the vertical orientation ones. Compared to the values given in prEN1993-1-3 [10], the actual mean longitudinal yield strength, equal to $f_{y,longitudinal,mean} = 438.82\,MPa$, is 9.7% higher than the nominal one ($f_{y,prEN1993-1-3} = 400\,MPa$) while the actual longitudinal ultimate stress $f_{u,longitudinal,mean} = 530.75\,MPa$ is 17.55% higher ($f_{u,prEN1993-1-3} = 450\,MPa$).

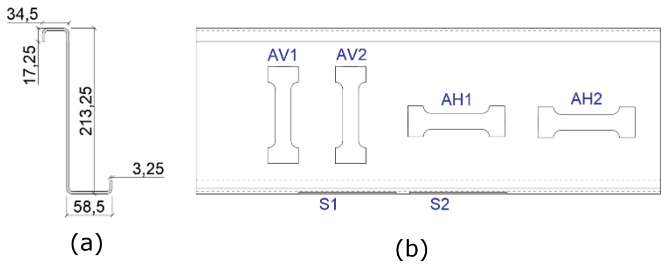

Figure 1 (a) Geometrical properties of the tested Z section and (b) orientation and notation of the extracted coupon samples

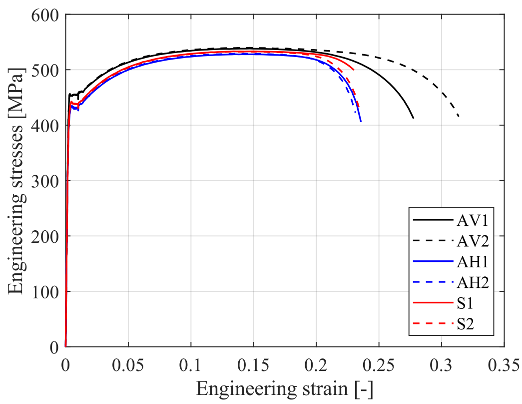

Figure 2 Stress-strain experimental curves

Table 1 Actual mechanical properties of HX420LAD steel grade

Sample	f_y [MPa]	f_u [MPa]	E [MPa]
AV1	456.7	538.22	204008
AV2	456.4	539.6	209514
AH1	434.7	527.9	200762
AH2	435.5	529.0	202887
S1	442.6	533.2	203548
S2	442.5	532.8	194374
Mean Value	444.7	533.5	202515

2.2 Set-up and instrumentation of "mid-span" tests

The objective of the first type of experimental tests is to induce a fatigue failure at the mid-span section of a simply supported Z-rail with a length of 1350 mm, as this section is the most loaded in terms of stresses creating by the bending moment around the strong axis. A 3D CAD presentation of the tested specimens is given in Figure 3.

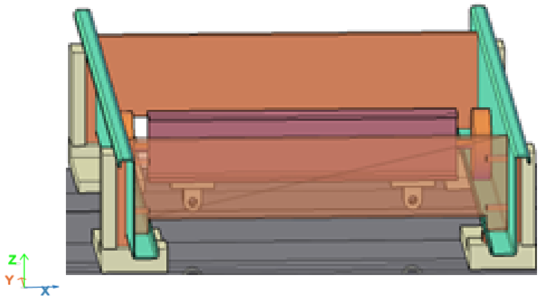

Figure 3 Mid-span test 3D view

As in a rack structure, the shuttle is running on the lower flange of two rails in mirror, two Z-rails (green members in Figure 3) are tested together. The load is applied, through the actual wheel of the shuttle, on the lower flange of the Z-rails, at a horizontal distance of 9 mm from the profile's web. The wheel, made of rubber and steel, has a diameter of 150 mm, a width of 38 mm and the thickness of the rubber is 10 mm around the circumference. In the test set-up, the wheels are rigidly connected to the extremities of a distribution beam (purple in Figure 3), to which the jacks are attached. As the wheel remains vertically, the torsional deformation is limited. Additionally, the out-of-plane displacement of the distribution beam is blocked.

For each specimen, one support is fixed in all displacements, while the other one is free to move in the longitudinal direction of the member (rolled support). For both supports, the rotation around X-axis is allowed while about Y and Z axis, forks restrained the rotations (see Figure 3 for the determination of the axes). To avoid any local instabilities due to the concentrated force at the supports, 30 mm stiffeners (orange in Figure 3), were placed on each side of the web. Those pieces restrained also the torsion of the Z-rail at the support, as it is the case in the real racking structure.

The load from the jack is applied through load control, with a frequency varying between 1 Hz and 2.5 Hz according to the intensity of the applied load range. Throughout the fatigue test, the load was measured using a reaction cell placed at the level of the jack while the displacement was obtained directly from the elongation of the jack. Additionally, for some specimens, strain gauges measuring the deformations in two perpendicular directions have been installed at the mid-span section, at two critical locations (from both sides of the radius corner between the lower flange and the web) numerically determined through a FEM analysis, which is not presented in this paper. For sake of simplicity, the two bi-directional strain gauges have been glued on the external face of the Z section just next to the corner, as indicated in Figure 4 by the red square. The specimens MS1-MS4, MS15-MS18 were instrumented (8 specimens in total).

Figure 4 Position of the strain gauges indicated with red squares

3 Fatigue at mid-span : Experimental results

3.1 Static test

Prior to the fatigue tests, a three-point bending test was performed to assess the behaviour of the Z-rails within the particular configuration. The objective of this test was to determine the load range intensity to be applied during the high cycle elastic tests subsequently. The force was implemented in a quasi-static manner until failure of one of the two specimens. This test ended due to a slip of the wheel, accompanied by a significant torsional and distortional deformation of the section at the position of the applied load, as shown in Figure 5.

Figure 5 Failure of the member due to excessive torsional deformation

As illustrated in Figure 6, the measured force is plotted against the vertical displacement for this static test. It can be observed that the maximum applied force was 22.24 kN for $MS1_{st}$ and 21.82 kN for $MS2_{st}$. The black dashed line in Figure 6 reflects the initial elastic stiffness of the $MS1_{st}$ F-u curve and it can be concluded that the Z-rail remains within the elastic range as long as the applied force does not exceed 11kN.

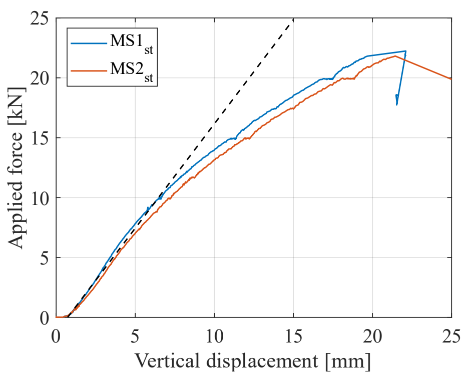

Figure 6 Mid-span quasi-static test results

3.2 High cycle elastic fatigue test

Among the 18 tested specimens (*MS1* to *MS18* – see Table 2), 16 were subjected to a constant load range varying from $\Delta P = 3.3$ kN to $\Delta P = 10.1$ kN so that no global yielding was reached. In order to investigate the fatigue behaviour of the beam against a high load range involving local yielding, the two remaining specimens (*MS5-MS6*) were submitted to constant load range higher than 11kN. By comparison with the actual load on the shuttle, it can be deduced that the shuttle transferred the pallet load using four wheels. Considering a total weight of 2000 kg [11], each load transferred 4.9 kN. It should be noted that high loads do not accurately reflect actual conditions; however applying such a load allows to obtain a point to be reported in the S-N curve for a high stress range.

Following the provisions of Masendorf et al. [12], the entire experimental campaign was performed by considering a constant load ratio of $\frac{P_{max}}{P_{min}} = 10$ for all tests. Table 2 summarizes for each tested Z-rail, the applied load range, the associated maximum and minimum load, as well as the number of cycles when the tests were stopped and the number of cycles corresponding to an increase of 10 % of the specimen displacement (see explanations here after).

Table 2 Experimental results of the mid-span tests

Specimen	ΔP [N]	Δσ [MPa]	Number of cycles – Tests sopped	Number of cycles – 10 % difference
MS1	3,328.43	171.17	Run out (2,800,000)	
MS2	3,337.34	171.63		
MS3	3,333.69	171.44		
MS4	3,331.43	171.33		
MS11	3,872.22	199.14	Run out (6,500,000)	
MS12	3,897.08	200.42		
MS13	4,554.94	234.25	1,274,345	1,055,150
MS14	4,579.58	235.52		1,212,622
MS15	4,595.58	236.36	Run out (3,500,00)	
MS16	4,598.27	236.48		
MS9	5,981.45	307.61	290,536	201,380
MS10	5,955.28	306.26		226,575
MS7	9,868.96	507.54	36,613	27,563
MS8	9,901.78	509.22		27,563
MS17	10,070.84	517.92	30,079	24,622
MS18	9,964.85	512.47		27,245
MS5	14,775.72	759.88	7,792	5,866
MS6	14,815.11	761.91		5,416

Throughout the experimental campaign, 8 tests resulted in "run out", meaning that no fatigue failure occurred even after a substantial number of cycles. Furthermore, it was observed that, for the same applied load, fatigue cracks developed in two Z-rails (*MS13-MS14*), while following a careful observation of specimens *MS15-MS16*, no such cracks were observed, even after a consequent number of cycles. This can be due to the material structure of the steel, a leading parameter in the fatigue behaviour [13].

As the tests were running continuously, the accurate number of cycles leading to a crack development was challenging to determine. For safety reasons, a displacement limit was imposed during the force-controlled test to prevent the failure of the entire system. Given the lack in the literature of a criterion to identify the number of cycles associated with the fatigue failure, a novel criterion is proposed here. This involve the derivation of the number of cycles to be reported in the S-N curve as a result of the number of cycle that corresponds to a 10 % increase in the specimen displacement. This is graphically represented in Figure 7 for the results of the *MS9* specimen.

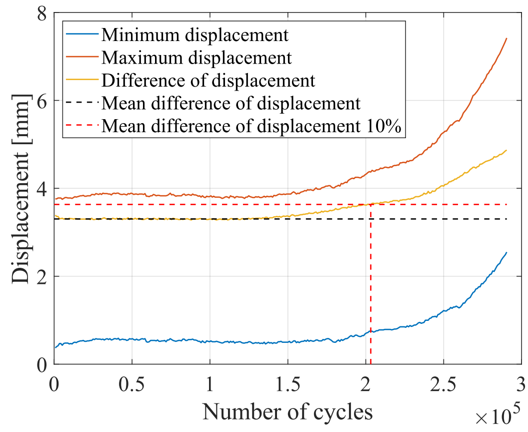

Figure 7 Number of cycles derivation criterion for MS9 specimen

For all specimens in which fatigue failure occurred, the crack initiates along the inner corner between the web and the flange on which the force is applied on the member's section. Then, the crack progresses towards the outer corner and, once is fully developed through the thickness, propagates towards the extremities of the specimens. This is illustrated in Figure 8 for *MS9* specimen, for which the evolution of the crack could be monitored. This highlights that local stresses responsible for the crack development are the transversal ones resulting from the relative opening of the flange compared to the web of the profile.

Due to the unfeasibility of strain measurement throughout the duration of the test, the strains were recorded after some specified number of cycles. This was achieved by stopping the test, loading the members in a quasi-static manner, and subsequently re-starting the fatigue test. Figure 9 shows the curves that link the vertical displacement with the measured micro strains for the gauge placed on the web that recorded the vertical strain for *MS18* specimen. It can be observed that the strain in the vertical direction on the web is decreasing as the number of cycles increases above 15,000 cycles, leading thus to a reduction of the stresses, and highlighting a loss of rigidity of the rail.

Figure 8 Fatigue crack pattern of specimen MS9 (number to be multiplied by 10^3)

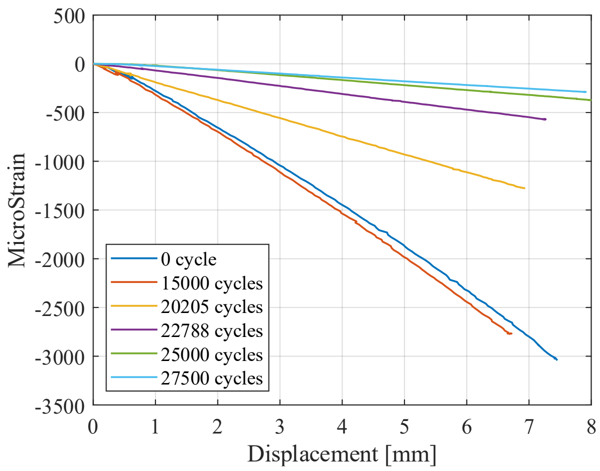

Figure 9 Strain measurement for the vertical gauge on the web

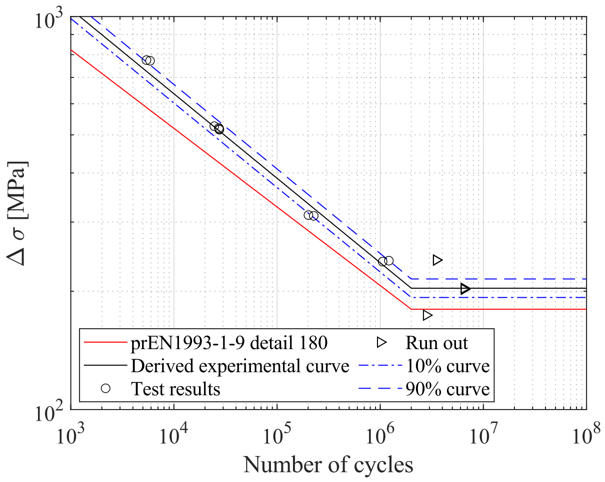

Figure 10 Derived S-N curves for the midspan detail

The experimental dot results reported in Figure 10 were derived by computing the stress variation from the strains measured in the non-damaged initial state (number of cycle = 0) of the specimen during one load cycle through the vertical gauge placed on the web. The strain was converted into stress by using the Hook Law (E = 206761 MPa). Subsequently, to extrapolate the results for the other specimens that were not instrumented with strain gauges, the mean value of the ratio between the applied force and the induced stress ($\Delta P/\Delta\sigma = 19.14$) was computed. Finally, by applying $\Delta\sigma = \Delta P/19.14$, the stress ranges for the other specimens can be computed.

In order to define, from the experimental results, the slope $k = 4.65$ and the constant amplitude fatigue limit $C = 1.09 \cdot 10^{17}$ of the S-N curve, the pearl string method provided in DIN50100 [14] has been applied, considering all the tests except the run out ones (*MS1-MS4, MS11-MS12, MS15-MS16*) and the yielded ones (*MS5-MS6*); the calculations are detailly explained in [8]. Additionally, to assess the accuracy of the test results, the standard deviation is computed by applying the recommendations available in the same code. The obtained standard deviation $\tilde{s}_{\log N_{corr}}$ is equal to 0.085. Finally, the scatter bands, computed for a failure probability of 10% and 90% are represented in Figure 10. It can be easily observed that the interval between those curves is very limited.

The obtained slope $k = 4.65$, is similar to the one proposed by prEN1993-1-9, for the characteristic fatigue resistance curve of a non-welded constructional detail subject to nominal stress ranges that corresponds to a light notch effect, for which *k* = 5. For indicative purposes, the red curve in Figure 10 corresponds to the available detail 180, the highest detail curve available in Figure 8.1(a) of prEN1993-1-9, but it should be noted that the computation of the stress for this normative curve and for the current curve is different (nominal stress vs. structural hot spot stress).

4 Comparisons and discussion

The experimental results obtained in the current research study have been compared to the ones of the FASTCOLD project [7]. Figure 11 presents the S-N curve resulting from the stress range derived for the 18 fatigue test performed for the downward loading situation compared to the one obtained in the current study. The stress ranges reported in the FASTCOLD project are computed based on a numerical model reflecting the experimental conditions using Abaqus software, considering the maximum principal stress at the crack location, while the reported number of cycles corresponds to a decreasing of 10% in the stress range measured by strain gauges at the level of the inner corner between the flange and the web, as FASTCOLD mentioned.

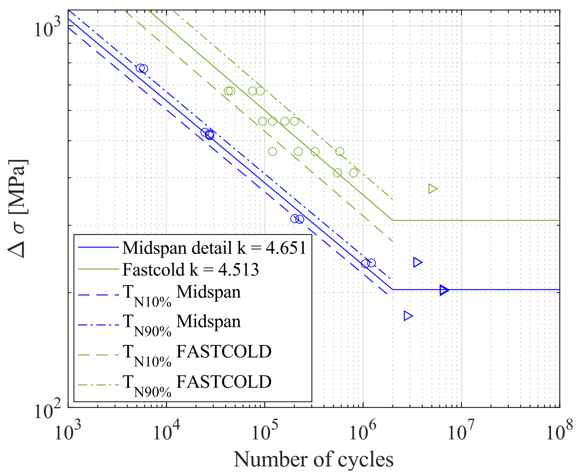

Figure 11 Comparison between results coming from the current research and FASTCOLD project

At first glance, it can be seen that the FASTCOLD curve (in green), is much higher than the one obtained in the framework of the presented research; this could be induced by the computation of the stress range as FASTCOLD applied the hotspot method and the current study the structural hot spot method. Furthermore, comparing the slopes of the obtained lines and the one proposed by the code, the current study (*k* = 4.65) gives a closest value to the one proposed by prEN1993-1-9 for a light notch detail, than FASTCOLD (*k* = 4.51). In addition, the standard deviations are smaller with $\tilde{s}_{logN,corr,mid} = 0.085$, than the ones obtained in FASTCOLD where $\tilde{s}_{logN,corr,FastCold} = 0.194$. Finally, the crack pattern is identical between the two experimental campaigns and the design recommendations are similar as both studies suggest to use a slope of *k* = 5 with a class detail of 180.

5 Conclusions

The fatigue behaviour of cold formed thin-walled rolling Z members with unequal flanges subjected to cyclic punctual loading on their larger lower flange was studied throughout this research. This loading configuration is typically observed in rack structures in which shuttles with pallets are in motion on such structural members used as rails. In a first step, static tests were performed in order to understand the behaviour of the members in those specific configurations. Then, in a second step, the fatigue life of two details was experimentally investigated (i) at mid-span of the member which is presented in this paper and (ii) at support (see [8]). In total, 34 specimens have been tested.

The main outcomes of this study can be summarized as follows:

- A consequent fatigue experimental campaign was conducted, studying two different details, during which 34 elements were tested, with a range of force intensity included between ΔP=3.33 kN and ΔP=14.81 kN resulting to a number of cycles that is included between 5,416 and 6,500,000;
- The fatigue crack is initiating at the level of the load application, in the inside radius of the corner between the web and the lower flange on which the load is applied; then the crack penetrates through the thickness to the outer radius and develops towards the extremities of the beam;
- The obtained crack pattern demonstrates that the failure appears due to the opening of the flange compared to the web of the section, independently of the test configuration;
- The slope of the experimental fatigue curve is similar to the one proposed by prEN1993-1-9.
- The investigated details could be designed against fatigue using the proposed fatigue midspan curve (Figure 10) and by computing the stresses according to $\Delta\sigma = \Delta P/19.14$.
- The experimental results and the design recommendations are in line with the ones found in the literature.

This research takes place in the framework of the Walloon Region project with the acronym ACTIONS studying the behaviour of rack structures. Relevant outcomes of this project can be found in [15]-[17].

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