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Fatigue Failure Mechanism of Steel Elements with Thin Webs

Mécanismes de rupture de fatigue des éléments en acier à paroi mince

Ermüdungsbrucharten von Stahlbauelementen mit dünnen Stegen

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SUMMARY

The paper contains the results of the extensive experimental investigation on the behaviour and failure mechanism of thin-walled steel elements subjected to repeated load. The presentation of recommendations and criteria for the limitation of slenderness of the web of hybrid plate girders is included as well.

RÉSUMÉ

L'article présente les résultats d'un vaste programme expérimental. Ce programme de recherche concerne le comportement et le mécanisme de rupture des éléments en acier à paroi mince sous charges répétées. Des recommandations sont faites et un critère pour la limite de l'élancement de l'âme de poutres mixtes est donnée.

ZUSAMMENFASSUNG

Der Beitrag behandelt Erkenntnisse aus umfangreichen experimentellen Untersuchungen hinsichtlich dem Verhalten und den Brucharten von dünnstegigen Stahlelementen unter wiederholter Belastung. Es werden Empfehlungen und Grenzwerte für die Schlankheit der Stege von hybriden Blechträgern vorgestellt.

1. INTRODUCTION

From the economical point of view it is necessary to design thin-walled steel elements. Therefore the design of steel elements with thin webs is recommended and demanded according to the elasto-plastic postcritical conceptions and limit state design method. Hybrid plate elements with different steels in flanges and webs of the cross-sections can be especially advantageous for economical design. For the safe and economical design of thin-walled hybrid steel elements it is very important to know their real load-carrying capacity and behaviour during repeated loading process. [1-3]

The thin webs of steel elements are laterally buckling under the static loading and they are laterally vibrating under the dynamic fatigue loading. As a result of this membrane and bending stresses occure which, together with residual stresses, can cause a formation and successive increase of fatigue cracks. Besides of that the thin webs of hybrid steel elements are loaded at the elasto-plastic stage. From practical point of view it is very important question of the limitation of the secondary stresses of webs in order to prevent arising of fatigue cracks during the life-time of elements. Therefore the extensive experimental programmes have been carried out for the investigation of load - stress - strain - deflection relationships and fatigue failure mechanisms of hybrid steel elements - girders and columns - with thin webs [4-6]. Similar investigations on girders were accomplished in the United States [7-8] and Japan [9].

According to this aim and allowable range the paper deals especially with realised investigation of hybrid plate girders.

2. EXPERIMENTAL INVESTIGATION

The complete experimental programme of the investigation consisted of the static and dynamic fatigue tests of 48 plate girders with symmetrical "I" cross-section of real practical dimensions, produced under common production-technological conditions. The test girders were different in geometrical dimensions, stiffened field ratios α, web slenderness β and material combinations of steels for flanges and webs (material and cross-section groups). One half of the test girders was used for static tests and the other half of similar girders for dynamic fatigue tests. Table 1 contains characteristics of fatigue test girders.

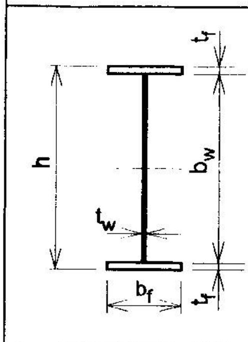
Cross-section	Dimensions $2\square b_f \times t_f +$ p. $t_w \times b_w$ (mm)	Span L (mm)	Stiffened field ratios $\alpha = a_w/b_w$	Slenderness $\beta = b_w/t_w$	Material combinations steel of flanges / steel of web			
					11 523.1	13 221.1	15 422.5	16 224.1
					11 375.1			
	$2\square 160\times 10(12)$ +p. 5×600	4900	1.0 1.25 1.5 2.0 3.5	120	A 125 A 126	B 123 B 124	C 125 C 126	D 123 D 124
	$2\square 180\times 12$ +p. 5×750	5950		150	A 155 A 156	B 153 B 154	C 155 C 156	D 153 D 154
	$2\square 200\times 12$ +p. 5×900	7000		180	A 185 A 186	A 183 A 184	C185 C186	D 183 D 184

Table 1. Characteristics of tested girders.

The cross-section dimensions in the individual groups were selected to give (at uniform t_w thickness and various b_w breadth values) slenderness ratios β_w of 120, 150 and 180. The flange dimensions were designed to ensure local stability. Element lengths were linked to b_w web breath ($L \approx 7b_w + 800$ mm). The intermediate panels had different side ratios ($1 \leq \alpha \leq 3.5$).

The flanges and webs were machine flame cut. Besides of that the tension flanges of girders were planed. The fillet welds between flanges and webs were made by automatic machine under flux, while stiffeners were hand welded.

Prior of testing the true geometrical and material characteristics of the flanges and webs were ascertained. All steels used for the experiments were in conformance with the requirements of the applicable standards, or exceeded them. The geometrical and material characteristics, as well as their corresponding deviations from design dimensions and standard material specifications are random variables. Hence, in evaluations of experimental results, either the directly determined or those generally probabilistically - statistically defined values of these variables could be used.

From the point of view of this investigation the information on lateral buckling of the webs in production and their influence on the overall behaviour of girders are particularly significant. Therefore, individualy tested girders were investigated for the lateral buckling of the webs in production. Scheme of girders and working arrangement of the tests are shown on Fig. 1.

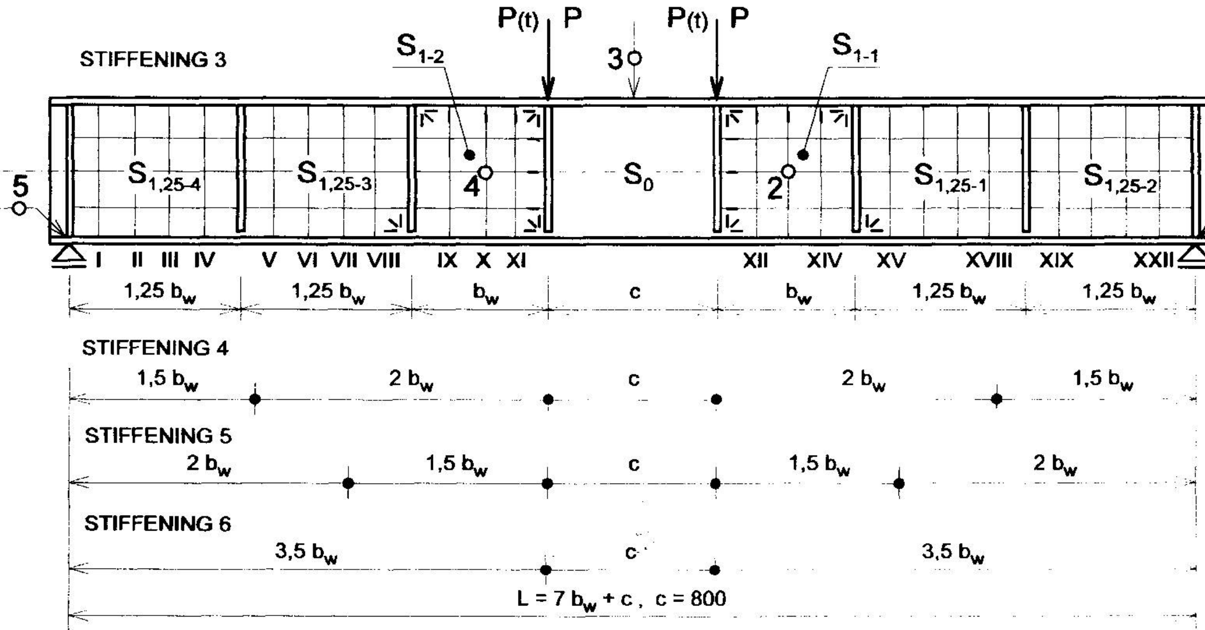


Fig. 1. Scheme of girders and working arrangement of the tests

The tested girders were sustained by special vertical and horizontal supports to prevent lateral buckling. The loading was realised by two hydraulic jacks. The tests of girders were divided into two parts. First of all, the girder was loaded by successive loading till to P_{max} and after that about five cycles between $P = 0$ and $P = P_{max}$ were repeated. Then the fatigue test could start. During fatigue test the girders were loaded by synchronise pulsate loads

$P(t) = P_0 + P_1 \sin(2\pi f t)$, where
$P_0 = 0.5(P_{max} + P_{min})$, $P_1 = 0.5(P_{max} - P_{min})$,
$P_{min} = (0.2 \div 0.4)P_u$, $P_{max} = (0.7 \div 0.8)P_u$, frequency $f = 5.0$ Hz,
P_u is the ultimate static loading including the elasto-plastic postcritical behaviour of the web

The behaviour of girders during the static and dynamic tests was ascertained by measurement, registration and evaluation of strains ε in the most stressed parts (78 tensometers). The supports sets down v_s - deflection pickups 1 and 5, deflection of girder v_c in the middle cross-section - deflection pickup 3 and buckling of the web w_w in the middle points of two stiffening panels - deflection pickups 2 and 4 were also measured. Besides of that we made the detailed measurement of static and dynamic buckling of the web w in different cross-sections and point - cross-sections I, II,..., XXII by movable pickup with graphic evaluation, or by inductive pickup, tensometer bridge and oscillograph, respectively.

The fatigue tests were realised in stages. After each 50 000 cycles the tests were interrupted. Incidental arising of the cracks was ascertained by the detailed observation of the girder with the help of magnifying glass and by direct graphic and tabulate evaluation of strains ε and deflections w_w and v_c at loads $P = 0$, P_{min}, P_{max}. The differences between last and previous values of strains ε in some points of girder indicate arising and placement of fatigue cracks. After arising of the cracks, we followed their development and influence on the global behaviour of girders. The tests continued until the total failure occurred.

3. BEHAVIOUR AND FAILURE OF TESTED GIRDERS

The thin webs of girders are laterally buckling in dependence on the initial imperfections, geometrical parameters and stiffness of bordered flanges and stiffeners. They are buckling in shapes which correspond to the mechanism of their behaviour according to the process of loading. These shapes are formed already at the beginning of loading process. In accordance with the initial shape a new service shape can be formed by the successive fluent transition or by the sudden jump over of the web. The service shapes of buckling are decisive for analysis of load-carrying capacity and behaviour of the thin webs of steel girders.

Under the dynamic fatigue loading the thin webs of girders are laterally vibrating. At the beginning of loading process the service shape of web vibration is formed in a similar way to the case of quasistatic loading. During the usual service loading regime in girders the resonant effects do not arise. Therefore, the lateral web deflections which are received at the repeating loading are practically identical with the dynamic lateral web deflections. Under the fixed cyclic loading the levels of deformations, deflections and shape of lateral web vibration did not change at any tested girder till the beginning of fatigue failure. Referred knowledge is presented in Fig. 2.

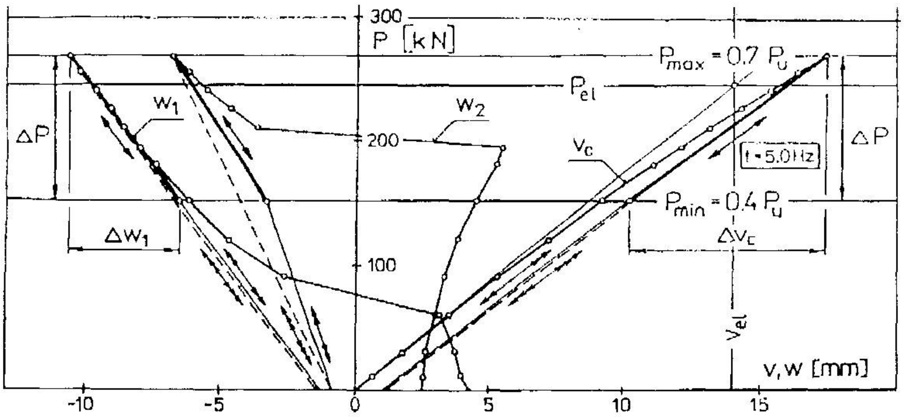


Fig. 2. Deflections w_1, w_2, v_c in dependence of load P. Jumps over of the web in the most loaded fields.

The ultimate load of the girder with account of the web buckling and the elasto-plastic postcritical behaviour of the web is $P_u = 382.2$ kN. During the first loading the sudden jump over appeared in two most loaded web fields - in the web field $S_{2\text{-}1}$ after $P = 60$ kN and in the web field $S_{2\text{-}2}$ after $P = 195$ kN. However, during the following repeating loading between $P = 0$ and $P = P_{max}$ (quasistatic loading) or between $P = P_{min}$ and $P = P_{max}$ (dynamic fatigue loading) any next jump over of the web did not appeared. Under repeating loading relatively quick stabilisation of deformations and deflections was set in and the web buckled or vibrated in the service shape. The girder failed by arising and quick development of fatigue crack in the tension flange after 1,000,000 cycles owing to production defect.

The result of realised experimental investigation proved that the lateral web vibration of steel girders can also cause the formation and successively increasing of the fatigue cracks. Fatigue cracks of the chosen test are presented in Fig. 3.

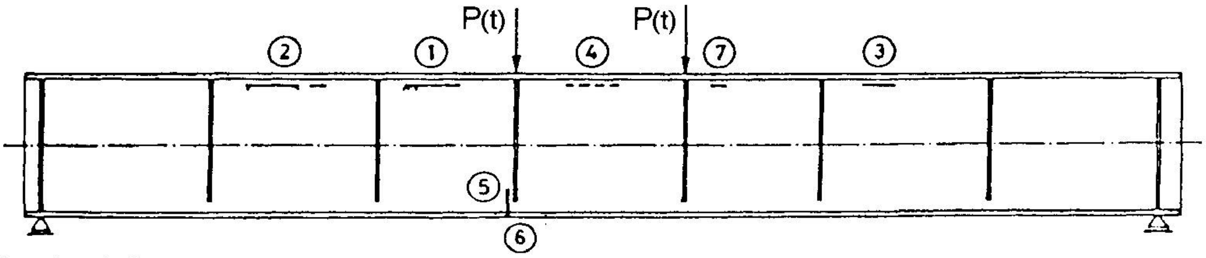


Fig. 3. Fatigue cracks in the thin web along welded connections with compression flange and transverse stiffener, crack in tension flange.

This girder is especially interesting with fatigue cracks along compressed flange in all internal web fields. The first cracks 1 and 2 had appeared after 300,000 and 400,000 cycles respectively. Later cracks were successively increasing, but only the initiation of the crack 5 along stiffener was decisive for the failure of the girder. The crack had spread very quickly to the tension flange in the form of crack 6 and the total failure of girder was completed after 1,342,000 cycles.

Seven fatigue cracks of 3 types have appeared in the girder. The crack of the type 1 is in the web under the compression flange, it is spreading along the fillet welding, it can pass also into the web depending from the membrane stresses. The crack of the type 2 is in the tension web part, it is passing along the stiffener to tension flange. The crack of the type 3 is in the tension flange, it appears after developing of the crack of type 2.

The intensity of the crack's propagation of different types of the cracks is the important factor of the complex life-time evaluation of steel girders. Due to our results there is difference in the crack's propagation velocity. The slowest cracks were those of the type 1, the fastest were cracks of the type 3.

Besides of mentioned fatigue cracks, which are characteristic for thin-walled girders, we could met also 2 another types of cracks as the results of production defects - e.g. due to defects in fillet welding, or due to the notch in the edge of tension flange.

4. LIMITATION OF WEB SLENDERNESS

According to the global results of realised investigation with taking account results of previous researches, the maximum slenderness of the web β_{uf} was designed for the steel girders subjected to fatigue loading in dependence on required life-time in cycles N and on calculated stress of flanges R_{df} (MPa):

$$\beta_{uf} = \frac{1760}{\sqrt[7]{N}} \sqrt{\frac{210}{R_{df}}} \; .$$

The values of the limit slenderness β_{uf} are in Table 2. It means that the slenderness of the web β should be less than β_{uf}. This limit criterion comes into consideration especially at the plate girders from high strength steels of homogeneous or combined cross-sections.

Life-time N (cycles)	Steel of flanges				
	11 375.1	11 523.1	13 221.1	15 422.5	16 224.6
	R_{df} (MPa)				
	210	290	352	424	548
	Slenderness β_{uf}				
100 000	339.80	289.16	262.46	239.14	210.35
200 000	307.77	261.90	237.72	216.60	190.52
500 000	270.01	229.77	208.55	190.02	167.15
1 000 000	244.55	208.10	188.89	172.10	151.39
2 000 000	221.50	188.49	171.08	155.88	137.12
5 000 000	194.32	165.36	150.09	136.75	120.29
10 000 000	176.00	149.77	135.94	123.86	108.95

Table 2. The limit slenderness of the webs β_{uf} for plate girders.

5. CONCLUSIONS

The realised tests have proved that the service shapes of buckling and vibration are decisive for the analysis of behaviour of thin-walled plate girders. The lateral web vibration of plate girders can cause formation and successive increasing of failure cracks which are situated near the welded connections of the web with flanges and stiffeners. Therefore, the fatigue strength of plate girders with thin web depends besides the usual loading, material and construction influences also on the lateral web vibration. Deformation and increasing of fatigue cracks in thin webs depends especially on the bending stresses along flanges and stiffeners and on their changes during loading process. The bending stresses of the web can be reduced above all by their slenderness β. Therefore, the web slenderness should be adequately limited according to presented proposals.

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