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The Quality of Butt-Welded Joints in Steel Railway Bridges in Szczecin

Abstract: This year marks the 40-th anniversary of Professor Andrzej Fabiszewski's death (1924–1978). He was a forerunner of the X-ray testing of butt welds in railway bridges in Poland. Professor Fabiszewski spent most of his life in Szczecin. The paper presents results of welded joint tests of 11 railway bridges located in the city of Szczecin. The results can be used for a new multi-level procedure of load-bearing capacity assessment of bridges in operation.

Keywords: welded bridges, radiographic tests, butt joints

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Introduction

When making a welded joint it is nearly impossible to entirely eliminate the formation of welding imperfections (WI). Joints which fail to satisfy the requirements of the PN-EN 1090-2 and PN-EN ISO 5817 standards should be repaired. It is generally recognised that the quality of joints after repair welding is lower than that of joints not subjected to repair. The foregoing results from the introduction of additional internal welding stresses [1]. The long-lasting operation of structures containing imperfections has revealed that repairs are not always necessary. The effect of a given welding imperfection on structural stability and durability should be analysed individually, taking into consideration structural solutions and loads affecting a given joint [2, 3]. In doing so, it is necessary to apply fitness-for-purpose (FFP) criteria making it possible to determine whether a welding imperfection is acceptable in in terms of cracking mechanics and the actual load affecting the joint [4, 5, 6].

A precursor of the fitness-for-purpose (FFP) idea in Poland was Professor Andrzej Fabiszewski (1924–1978). Thanks to Professor, in the years 1954-1990, X-ray tests of butt welds of girders in approximately 200 railway bridges (in operation) were performed within the confines of task MK 133-06-02-04 commissioned by the Ministry of Transport [3, 6, 7].

The year 2018 marks the 40th anniversary of Professor Fabiszewski's death. To commemorate this occasion, the research workers of the Department of Metal Structures of the West Pomeranian University of Technology in Szczecin wish to present in more detail the research activity of Professor Fabiszewski, a multi-annual head of the Institute of Steel Building Engineering of Szczecin University of Technology (SUT) and a person responsible for in-situ tests of steel bridges. Professor started X-ray tests of railway bridges in 1954. The test results were published in technical journals and Scientific Bulletins (Zeszyty Naukowe) of the SUT [8, 9, 10]. On 2

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and 3 June 1958, the Institute of Steel Building Engineering of the Szczecin University of Technology along with the NDT Committee of the Polish Academy of Sciences (PAN) organised (in Szczecin) a conference entitled Radiographic Structural Tests. An introductory paper was presented by Professor Stanisław Bryl [11]. Professor Andrzej Fabiszewski presented a paper [12] concerning test results related to welds in the first ten railway bridges (40 girders and 984 X-ray photographs). The above-named tests might have inspired Professor Fabiszewski to write a monograph concerning welding imperfection-induced brittle cracks [13].

Systems for Assessment of Load-Bearing Capacity of Bridge in Operation

The fitness-for-purpose (FFP) criteria recognised joints as the weakest structural points. Since the 1970s the above-named approach has been applied in relation to gas pipelines and pressure vessels and incorporated in several globally used standards. The precise FFP criterion is presented in [1]. According to the above-named publication *The fitness-for-purpose criterion involves the application of crack mechanics-related calculations to identify acceptable sizes of welding imperfections without compromising the required structural stability*. Figure 1 presents the welding imperfection-related acceptance level according to the above-named method. The method requires that welded joints be subjected to a precise NDT-based quality check aimed to identify the critical size of a welding imperfection initiating the propagation of a crack. The determination of the size of the critical imperfection and the methodology applied when identifying acceptable sizes of welding imperfections in bridges is presented in publication [14].

The tests revealed that, in many cases, operated bridges failing to meet the criteria of design standards could safely transfer service loads without the necessity of reinforcement. In the years 2003-2011, a new method enabling the assessment of the load-bearing capacity of existing bridges was accepted in Great Britain, Denmark, Switzerland, Canada and USA [15, 16]. In comparison with the FFP (fitness for purpose) method, the above-named new method

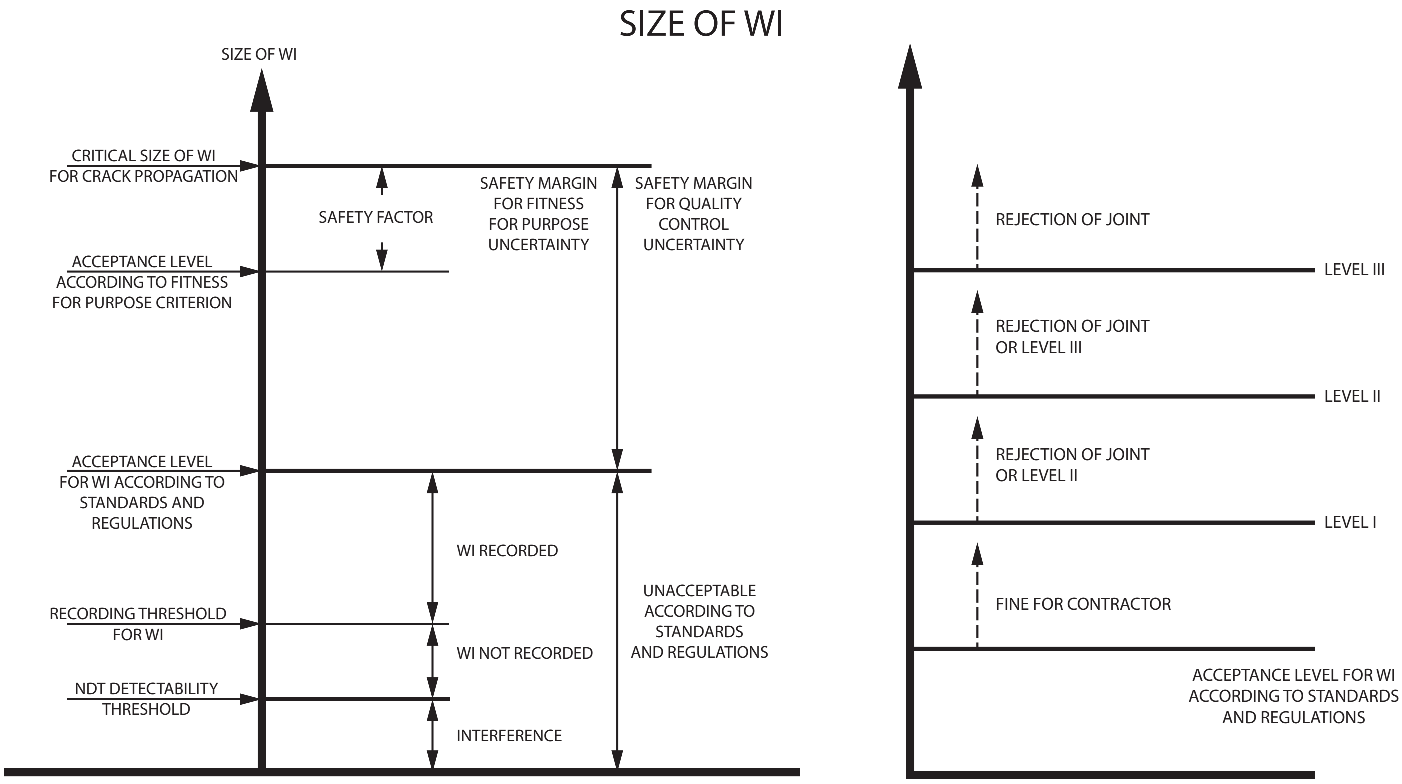


Fig. 1. FFP acceptance levels: a) in accordance with fitness for purpose (FFP) criteria, b) in accordance with the British PD6493 standard [1]

enables more detailed and reliable assessments of bridge load-bearing capacity (Fig. 2).

The overview of individual requirements and the manner of their application according to standards used by countries using the new assessment of bridge load-bearing capacity is presented in publications [15, 17]. As can be easily seen, each level related to the assessment of bridge load-bearing capacity requires the knowledge concerning the quality of welds, the tests of which are presented in this paper. The tests were limited to bridges situated in Szczecin as in this city professor Fabiszewski spent most of his professional life.

Non-Destructive Tests of Railway Bridges in Szczecin

In the years 1957-1984, the Department of Metal Structures at Szczecin University of Technology (today's West Pomeranian University of Technology in Szczecin) performed X-ray tests of butt welds in 11 railway bridges located in Szczecin. Table 1 presents basic specifications of the above-named bridges. The bridges are listed chronologically (according to the date of construction). Except for truss bridge no. IX located at the reservoir of the river Oder, the remaining structures are railway bridges having plate girder-based structures and located over

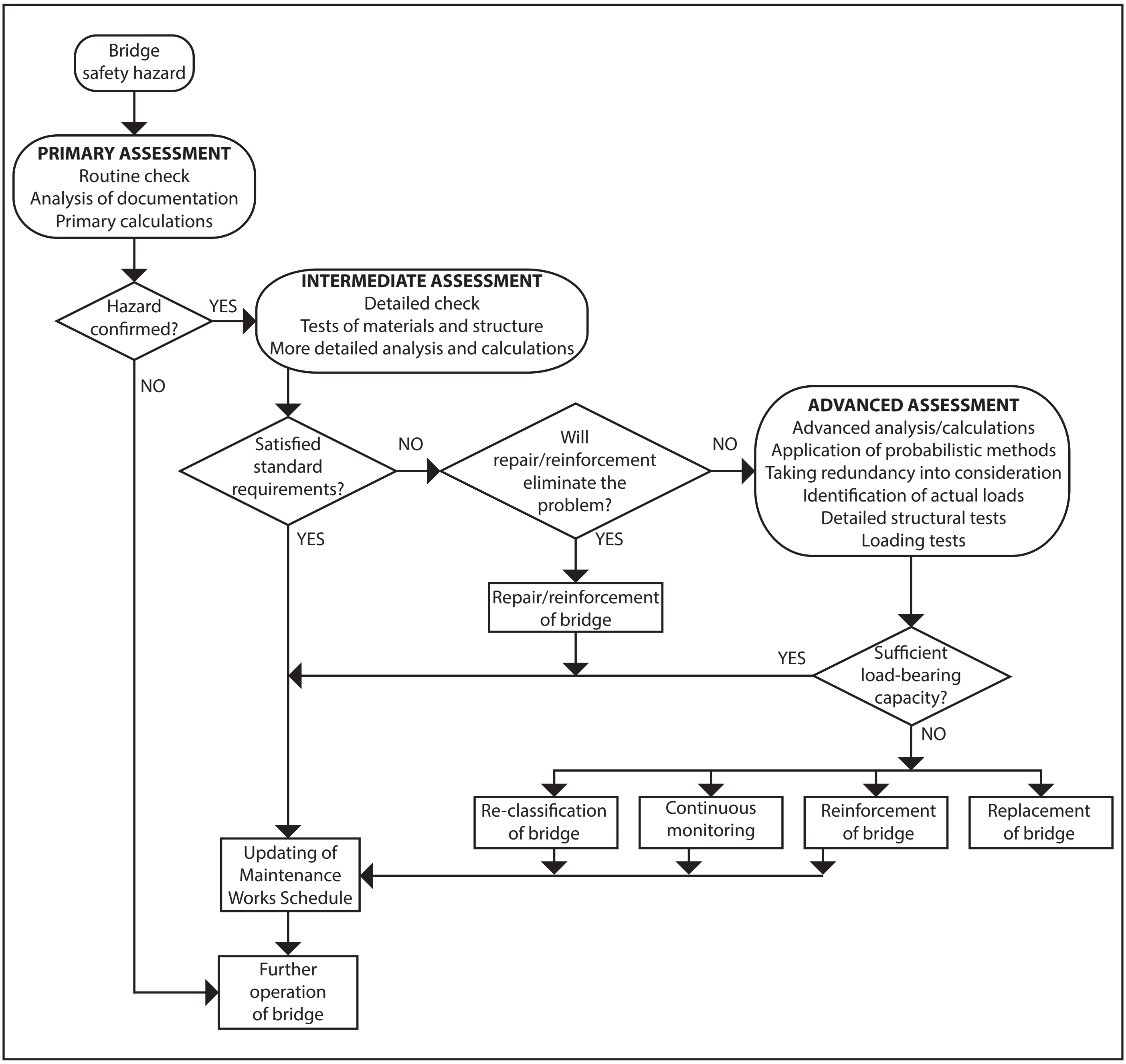


Fig. 2. Multilevel procedures used when assessing the load-bearing capacity of in operation [17]

the city streets (Fig. 3). The bridges were subjected to the tests between 1 and 4 times. In total, the bridges were subjected to tests 18 times. The tests involved the taking of 821 photographs of butt-welded joints, i.e. 344 in the compressed zone and 477 in the extended zone.

In cases of lattice girders, the tests involved the extension joints of lower belts located near fixing nodes. In cases of plate girder-based structures, the tests involved the butt welds of upper and lower belts and the webs of load-bearing girders. In accordance with the regulations of the then valid PN-64/M-69772 standard, the X-ray photographs of the welds in individual bridges were related to appropriate imperfection classes R1–R5. Presently, the above-named imperfection classes correspond to weld-related quality levels B+, B, C, D and >D specified in PN-EN ISO 5917:2014. The aforesaid quality levels were used to assess the welds of the bridges

Fig. 3. Bridges subjected to the tests (bridge no. VI, VII and VIII of the identical structure)

Table 1 Specifications of bridges and X-ray tests

Railway line	Bridge no.	Year of construction	Year of tests	Number girders	Number X-ray	Number cracks	Structure (Fig. 3)
1	2	3	4	5	6	7	8
Poznań-Szczecin	I	1935	1971, 1984	7	54	11	7 frames
	II	1936	1958, 1962 1969, 1983	4	100	36	plate girders
	III	1948	1957, 1993	6	132	75	plate girders
Szczecin-Trzebież	IV	1948	1957, 1983	2	36	–	plate girder three-span plate girders
	V	1958	1971, 1983	2	45	–	
Wrocław-Szczecin	VI	1964	1984	4	14	–	plate girders
	VII				42		plate girders
	VIII				88		plate girders
SPa-SPd-Nabrzeże Czeskie	IX	1964	1984	6	78	–	latticework (truss)
Zdroje-Podjuchy	X	1972	1984	2	16	–	plate girders
Poznań-Szczecin	XI	1977	1984	6	216	–	plate girder two-span

Table 2. Numerical list of X-ray photographs divided according to quality levels

Bridge number	Number of X-ray photographs in relation to a quality level (with cracks)						
	compressed zone		extended zone		in total		ΣX-ray
	B+, B, C	D and >D	B+, B, C	D and >D	B+, B, C	D and >D	B+ – >D
1	2	3	4	5	6	7	8
I	11	20 (4)	4	19 (7)	15	39 (11)[1)]	54
II	2	38 (24)	11	49 (12)	13	87 (36)[2)]	100
III	11	63 (44)	7	51 (31	18	114 (75)	132[3)]
IV	–	20	–	16	–	36	36
V	23	–	21	1	44	1	45
VI	–	–	14	–	14	–	14
VII	6	–	36	–	42	–	42
VIII	4	–	84	–	88	–	88
IX	–	–	78	–	78	–	78
X	8	–	8	–	16	–	16
XI	138	–	78	–	216	–	216
In total	203	141 (72)	341	136 (50)	544	277 (122)	821
% in ΣX-ray	24.7	17.2	41.5	16.6	66.3	33.7	100

1) All of the cracks in the joints made during repairs after wartime damage in 1946 [18]
2) Cracks in interfaces of webs made after failures during assembly in1935 [19]
3) In 1957 132 photographs were made; in 1984 107 photographs were made; in 1958 6 interfaces were riveted in the upper belt and 7 interfaces were riveted in the lower belt

in Szczecin (see Table 2). The welds of the compressed zone and of the extended zone of a given bridge were divided into two groups, i.e. a group representing quality levels B+, B and C (satisfying the quality requirements specified in PN-82/S-10052 related to good quality welds) and a group including joints unacceptable in new structures, i.e. representing quality levels D and >D. In total, 277 weld segments were included in the second group, i.e. 33.7% of the total number of welds subjected to the tests.

The above-presented number includes 141 segments of butt welds in the compressed zone and 136 segments of welds in the extended zone. One hundred and twenty two (122) X-ray photographs (14.9% of all of the photographs taken) revealed weld cracks of various lengths (Fig. 4). In addition to the cracks, the primary welding imperfections disqualifying the test welds included the lack of penetration and slag lines. Weld cracks were revealed in bridges number I, II and III built in the years 1935–1948 (see Table 1). Welds representing significantly higher quality were revealed in the bridges built in the years 1958–1977, i.e. number V–XI. Apart from one X-ray photograph in bridge number V, all the remaining 498 X-ray photographs of the above-named bridges revealed welds representing quality levels B+, B and C (99.8% of the photographs taken in the objects).

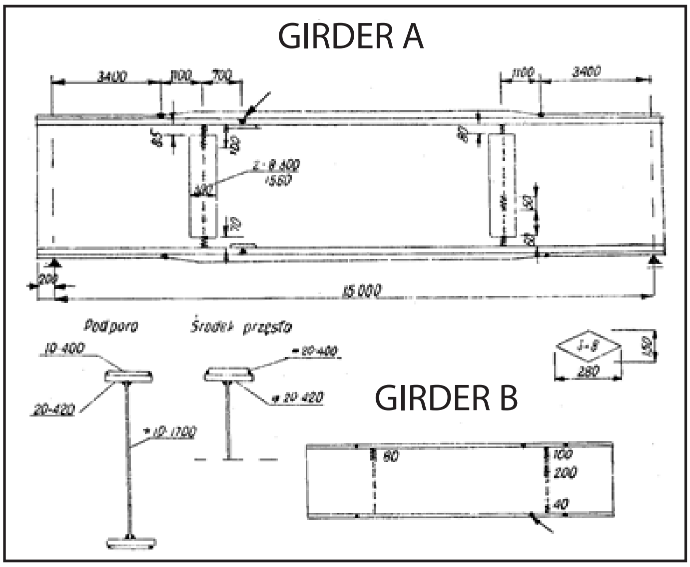


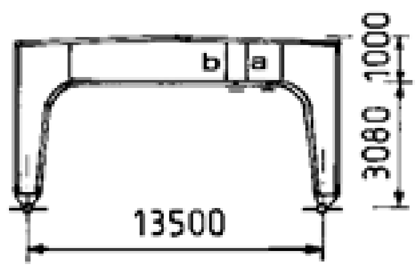
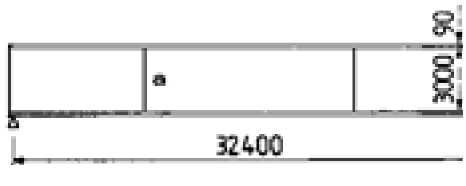
Fig. 4. Girders A and B of track no. 1 of bridge no. III with cracked welds [12]

Particular attention should be paid to railway bridge no. II. The load-bearing structure of the single-span double-track upper-ride railway bridge was composed of freely supported welded plate girders having parallel belts and a span 32.40 m. The web having a thickness of 16 mm was 2750 mm high. The belts characterised by the same width of 400 mm and a thickness of 90 mm were made of continuous bulb plates (Wulst-Flaschstahl); the Dörnen system, type II [19]. The individual girder had two vertical interfaces of the web, located 10.0 m away from the axis of the support bearing. Only girder C in track no. 1 (because of a failure during assembly in 1935) was subjected to cutting performed to remove cracked joints of the web and provided with new inserts having a width of 500 mm. As a result of the above-presented repair, the girder had four vertical welds of the web. In spite of a meticulously developed technology and a carefully performed repair, new joints revealed the presence of longitudinal and transverse cracks. The photographs revealed 33 cracks in the vertical joints of girder C and 3 cracks in the joints of girder D. Germans left the interfaces without reinforcement, recommending the performance of periodic X-ray tests. Repeated tests (five times) did not reveal the propagation of the previously detected cracks [20].

Stresses in Welds in the Two Oldest Railway Bridges of 1935 and 1936

To get to know actual stress values in the primary girders of object no. II, in September 1962 the Railway Research Institute (then known as the Railway Scientific and Technical Centre in Warsaw) performed extensometric tests under static and dynamic loads. Stresses were measured in the direct vicinity of the web joint welds containing cracks (x = 10.25 m) and at the half of the railway bridge span (x = 16.20 m). The mean stress value of three measurements in relation to the load exerted by two steam locomotives PT-31 (coupled by means of tenders) is presented in column 6 of Table 3. Column 3 of Table 3 presents stress values related to the static load, whereas column 4 presents stress values related to the static load and standard loads taking into consideration dynamic effect. Standard stresses were determined in relation to the primary system of loads adopting load class k = +2. Column 5 presents values of calculated stresses from static loads and dynamic loads exerted by locomotive ET21 in relation to bridge I [18] and two steam locomotives PT31 with full tenders (170 kN) in relation to bridge no. II. In each case, locomotive or steam locomotive-induced stresses were multiplied by the dynamic coefficient. Column 7 presents values of quotients of calculated stresses $\lambda = P_{eksp}/P_{norm}$, restricted within the range of 0.618 to 0.694. According to publication [3], in relation to the nine analysed bridges the above-named quotients were restricted within the range of 0.53 to 0.70. To provide the full picture of the values of the stresses in the butt joints with internal cracks, column 8 presents the value of unlimited fatigue strength determined in individual tests Z_{rj} = 90 MPa. The above-named value constituted approximately 72% of value Z_{rj} = 125 MPa in relation to the butt joints representing quality level B+–D [3]. In all of the plate girder bridges, the values of service stresses in the welds with internal cracks were lower than fatigue strength Z_{rj} $(\Delta\sigma_C)$ = 90 MPa.

Table 3. Schemes of the girders and normal stresses related to characteristic loads in the butt weld and their fatigue strength Z_{rj}

Bridge no.	Schematic girder and location of the joint containing cracks	Stresses in MPa				$\lambda = P_{eksp}/P_{norm}$	Z_{rj} [6)] MPa
		static loads	system of loads		measured		
			P_{norm}	P_{eksp} [1)]			
1	2	3	4	5	6	7	8
I		$\sigma_a = 6.8$	44.2	27.3	–	0.618	90.0
		$\sigma_b = 11.6$	67.2	42.3	–	0.629	90.0
II		$\sigma_a = 24.0$	89.8	62.3 [2)]	22.3 [3)] 28.4 [4)] 29.6 [5)]	0.694	90.0

1) locomotive ET21 + static load,
2) 2 steam locomotives Pt31 with tenders 32D29 + static load,
3) static load 2×Pt31 with tenders
4) dynamic load – v = 20 km/h,
5) dynamic load – v = 80 km/h,
6) Z_{rj} according to individual research [3]

Summary

1. The bridges built in the years 1935–1948 were characterised by a particularly bad condition. Four bridges subjected to tests by making 322 X-ray photographs, out of which 276 (i.e. 85.7%) presented quality level D and >D. In turn, 7 bridges built in the years 1958–1977 were subjected to tests by making 499 X-ray photographs, out of which only 1 (0.2%) presented quality level D.
2. Putting railway bridge no. II into operation after its failure in 1935 with 36 internal cracks in the vertical butt joints of plate girder webs (16×3000 mm in cross-section) was found by the authors as a significant technical surprise. Repeated tests (5 times) of the welds did not reveal the propagation of cracks or the formation of new ones.
3. The non-destructive tests of the welds in the bridges revealed that structural cracks were permissible as long as they did not increase during operation or as long as their propagation was restricted within the range not posing a risk to structural strength and rigidity.
4. PN-EN 1993-1-9:2007 is the first standard according to which *Fatigue cracks formed during operation do not necessarily mean the end of the operation of a structure. Cracks should be removed with the highest care, avoiding sharper notches.* The above-presented approach was confirmed by laboratory tests of analogous welded joints [3]

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