The Impact of Residual Stresses on Bogie Frame Strength

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Abstract The article describes a method for determining the residual stresses occurring in the structure of a railway vehicle bogie frame. The performed tests involved the application of the destructive strain gauge method. The impact of residual stresses on bogie frame strength has also been determined.

Introduction

Residual stresses appear during most technological processes, and their value and distribution down through the material have a significant impact on fatigue strength and wear, etc. Residual stresses were determined for a railway vehicle bogie frame that had been earlier subject to standard static load and fatigue tests, in accordance with [1] and [2]. After removing the frame from the fatigue test stand, it was subject to a cutting process. Stresses were determined for 14 strain gauges stuck to the smallest possible elements of the frame to make it possible to assume that the residual stresses occurring within the frame were completely released before the frame was cut.

Since the tests were confidential, we are not able to include the outline of the arrangement of the strain gauges or any drawings or pictures of the frame.

Table 1. Strain gauge location on the frame

Strain gauge no.	Strain gauge location on the frame
T1, T17	Bottom flange of the longitudinal member, ¼ of the distance from the end point
T2, T18	Bottom flange of the longitudinal member, ¼ of the distance from the end point
T3, T11, T19, T27	Top flange of the end of the I-beam included in the headstock near the joint
T4	Near the joint connecting the cross beam with the longitudinal member - top flange
T5	Near the joint connecting the cross beam with the longitudinal member - top flange
T6	Near the joint connecting the cross beam with the longitudinal member - bottom flange
T7	Near the joint connecting the cross beam with the longitudinal member - bottom flange
T8, T24	Cross beam near the bump stop support

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Attention: tension gauges marked by the same color in the table are symmetrical relative to the longitudinal or the transverse axis of the frame.

Materials and methods

Description of the procedure for determining residual stresses

Test method. An original test program involving the use of the destructive strain gauge method was applied. The program was developed based on the experience gained during tests of the frames of railway vehicle bogies and when determining the stresses occurring in their respective structures. During the frame cutting, the stresses were recorded using a strain gauge system designed for fatigue testing. Fourteen TF-5/120 strain gauges manufactured by TENMEX were used.

Description of the procedure followed during frame cutting.

Phase 1 – Cutting the headstocks.

Phase 2 – Cutting the headstocks off and cutting the frame into two large parts.

Phase 3 – Cutting a part of the frame using a panel saw. The process resulted in frame-shaped elements, with a maximum of four tension gauges affixed to each of them.

Phase 4 – Cutting the tension gauges from the frames (Fig. 1). The result was a set of small elements, each with an affixed tension gauge.

The tension gauges were reset before each cut. Stresses were recorded throughout the entire duration of cutting process and for some time after it was finished, until the temperature of the frame and the ambient temperature became stable (i.e. until the strain / stress values registered at the bridge stabilized). If it appeared necessary to disconnect the wires between the tension gauges and the bridge, the reading was recorded and the tension gauges were reset again before the next cutting phase. The procedure was repeated for each following cutting operation, regardless of the tools used. The residual stresses for a given tension gauge were calculated as the sum of the stresses following each cutting operation with a reverse symbol. The values of these residual stresses are given in Table 2.

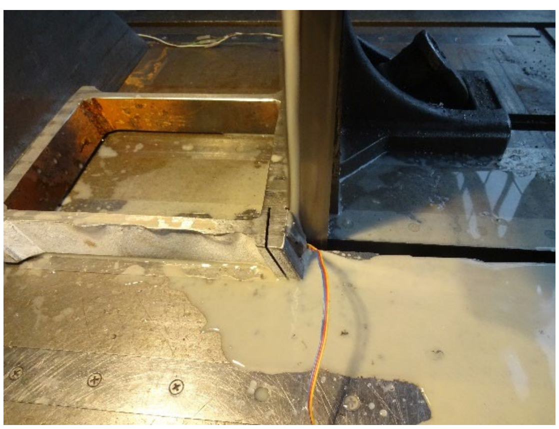

Fig. 1. Phase 4 – the last strain gauge cutting operation. Cutting the strain gauge out of the frame.

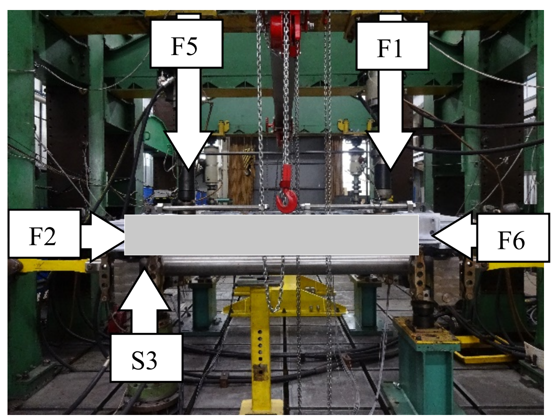

Fig. 2. The frame at the test stand where static load testing was performed

The following tools were used in the course of the above-mentioned operations: an angle grinder, an acetylene torch, a Marvel Armstrong – Blum Mfg.Co Series 8 Mark II panel saw. The occurring strain was recorded using a strain gauge module: NI PXIe-4330 + 4 × 8CH BRIDGE

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INPUT NI TB-4330 – National Instruments [9] and the following strain gauge bridges: UPM-100 Hotinger Baldwin Messtechnik Darmstadt and STRAIN INDICATOR P-3500, Vishay – Measuremets Group – Instruments Division – Raleigh, North Carolina, USA.

Before the frame was cut, nine static load tests – labeled A01 to A09 – were performed. A simplified diagram of the loads and the values of the applied forces are given in Fig. 2 and Table 2. Every load had a corresponding file for which the name included the name of a given load. The files also included the strain gauge numbers and the recorded stress values assigned to the strain gauges. The files were processed following the standard procedure applied in frame static load testing. Each measurement point (strain gauge) had a σ_{max} , a σ_{min}, the average stress value $\sigma_m = (\sigma_{max} + \sigma_{min})/2$, and the UF value determined based on recommendations [5]. A Goodman diagram was developed and safety factors were determined according to [3]. Next, the values of the residual stresses from Table 3 were added to the stresses resulting from frame loading. The operation was performed for each of the nine loads. This produced new files with stress values, labeled B01 to B09. The values were processed in a similar manner in an analogous manner to the previous ones. The data obtained as a result was used as reference material, on the basis of which the impact of residual stresses on the frame strength was determined.

Table 2. Forces affecting the frame – values like at the 3rd stage of fatigue loading.

Force labeling according to Fig. 2		load 1, A01	load 2, A02	load 3, A03	load 4, A04	load 5, A05	load 6, A06	load 7, A07	load 8, A08	load 9, A09
F1	kN	-123.4	-123.4	-154.2	-154.2	-92.8	-92.8	-61.8	-61.8	-100.0
F2	kN	+103.4	+103.4	0	0	0	0	0	0	0
S3	mm	-3.2	+3.2	-3.2	+3.2	-3.2	+3.2	-3.2	+3.2	0
F5	kN	-154.2	-154.2	-123.4	-123.4	-61.8	-61.8	-92.8	-92.8	-100.0
F6	kN	0	0	+103.4	+103.4	0	0	0	0	0

Vectors on Fig. 2 indicate the directions of the applied forces and the actuator labels as used in Table 2. The sense of the vector represents negative force (compression) in Table 3.

Results

Table 3. Residual stresses for individual strain gauges

Testing gauge no.		**T1**	**T17**	**T2**	**T18**	**T3**	**T11**	**T19**
Residual stresses within the frame	MPa	+16.8	-46.3	-40.1	-75.5	-61.1	+68.8	-4.1
Testing gauge no.		**T27**	**T4**	**T5**	**T6**	**T7**	**T8**	**T24**
Residual stresses within the frame	MPa	+76.2	+120.8	-11.1	-50.7	-1.6	+122.3	+87.5

The performed tests showed that the highest and lowest residual stresses were registered by the following strain gauges: T8 (+122.3 MPa), T4 (+120.8 MPa), T24 (+87.5 MPa), T17 (-46.3 MPa), T3 (-61.1 MPa) and T18 (-75.5 MPa). Out of the fourteen examined points, six had tensile stresses (+) determined, and eight had compressive stresses (-) determined. In the case of two compressive stresses, their values are: - 4.1 MPa for T19 and -1.6 MPa for T7, which means they are below the measurement error threshold. It can be roughly assumed that, in the set of the tested tension gauges, half of the measurement points were subject to positive stresses, and the other half to negative stresses.

It is important to bear in mind that the values of the forces occurring during static loading (A01 ÷ A09) corresponded to the 3rd stage of fatigue loading (at Stage 3, the force amplitudes are 40% larger than at Stage 1) – the principle that UF needs to be below 1 cannot therefore be applied since it pertains to forces corresponding to the 1st stage of fatigue loading. Likewise, the safety factor determined based on the Goodman method cannot be greater than 1. It should be mentioned that the residual stresses occurring within the frame were determined after fatigue testing of the frame. Three stages of fatigue tests in accordance with UIC-615-4 were completed, yielding a total of 10 million loading cycles. This could have an impact on the values of residual stresses (there might have been a relaxation of residual stresses).

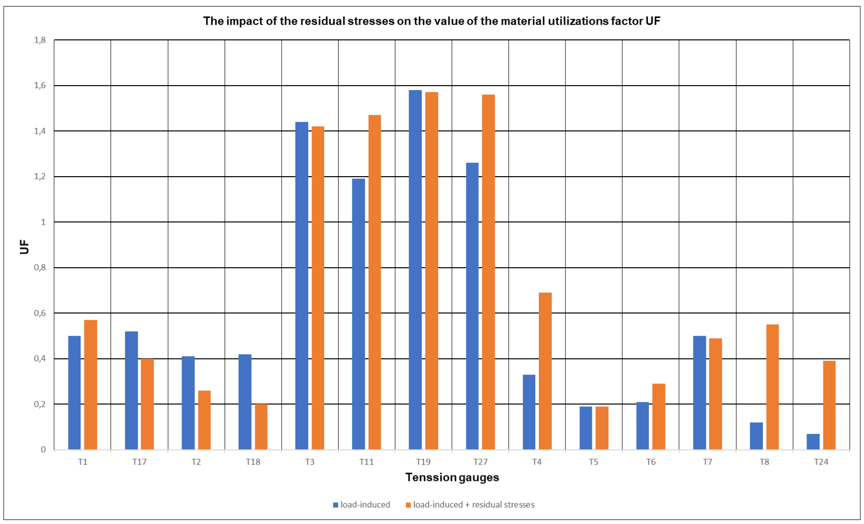

Fig. 3. Illustration of the change in the UF factor before and after adding residual stresses.

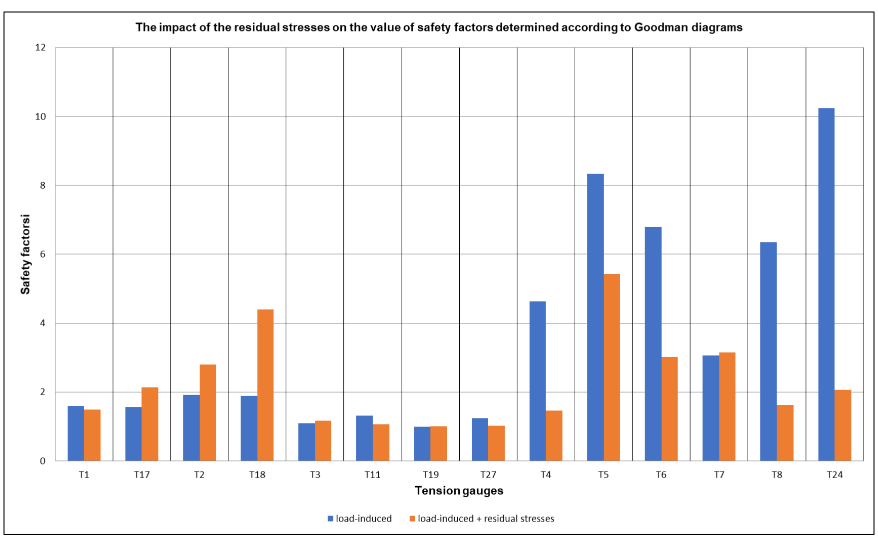

Fig. 4. Illustration of the change in safety factors determined on the basis of a Goodman diagram.

Analysis

1. Residual stresses were determined for 14 strain gauges fixed to a bogie frame in order to make it possible to determine the stresses generated by static and fatigue loads. Strain gauges are usually fixed to the frame in a way that their directions correspond to the directions of principal stresses generated by loads. It is unlikely for these directions to correspond to principal directions resulting from residual stresses. That is why, in order to make such tests more reliable, it would be reasonable to affix strain gauge rosettes to the frame.
2. It was noticed that the residual stresses recorded for symmetrical strain gauges had different values. This is probably due to the manufacturing technology of the frame (different welding order, different process and different force of restraint during welding).
3. When analyzing Fig. 3. "The impact of residual stresses on the value of the material utilization factor UF", the following was found: an increase in the UF value in 7 out of 14 cases (deteriorated strength), one case of the UF remaining unchanged, and a decrease in the UF value in 6 cases (improved strength).
4. Based on Fig. 4. "The impact of the residual stresses occurring within the frame on the value of safety factors determined according to a Goodman diagram", the following observations could be made: an increase in the safety factor value in 6 cases (improved strength) and a decrease in the safety factor value in 8 cases (deteriorated strength).
5. It was found that T19 was the most strained point out of all fourteen points with strain gauges fixed to them. It was proven in both of the analyses performed according to DVS 1612 and ERRI B12/RP 17, 8th Edition, Test programme for wagons, bogies, bogie frames, UTRECHT, April 1997.
6. At some points, the residual stresses changed the safety factor values to a significant extent – see Fig. 4. But most of those points were not significantly strained and, after the residual stresses were added, they were still on the safe value side of the figure. In the case of the most strained point (tension gauge T19), the safety factor value even grew – from 0.99 to 1.01.
7. Similar observations can be made when we analyze Fig. 3. The material utilization factor value UF for T19 improved from 1.58 to 1.57.
8. In two cases (strain gauges T11 and T27), the strength deteriorated significantly after residual stresses were added. This can pose a threat to the safety of the frame – see Fig. 3 and Fig. 4. This is proven especially by analysis carried out in line with DVS. After 10 million fatigue cycles performed in accordance with UIC-615-4, no cracks were found at those points, though.

Conclusions

The conducted tests have shown that the values of residual stresses occurring in bogie frames are in the same range as load-induced stresses. Therefore, they have a great impact on the strength of the structure they affect. So far, the tests and calculations for frames have been performed mainly in terms of loads, often disregarding the significance of residual stresses. When analyzing the findings of frame static tests, the impact of residual stresses should be taken into consideration. However, this is not really practicable at present. This is why fatigue tests play such a great part in evaluating frame strength. Strain gauges are fixed to frames to make it possible to control the stresses during static and fatigue loading tests. This is why, out of over thirty frames tested over the past 20 years at the Railway Institute, only one frame has had a crack on it in the location of a tension gauge. Other frames would crack where there were no tension gauges, and where the

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stresses and their load amplitudes were often minor, which is proven by the earlier MES calculations. The cracks could have been caused by residual stresses combined with load stresses and the impact of the notch effect. The case was similar with the frame tested as described herein. The tests in question were performed when performing the obligatory functional on-site tests of bogie frames, as required under the regulations in force. For this reason, the occurring stresses were determined only at 14 points, i.e. where tension gauges were fixed. This is why the probability of locating a point where significant residual stresses would combine with significant load stresses was very small.

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