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Stress Relaxation in Copper Bolted Busbar Assemblies with New Design Concept of the Bolt Holes

Abstract. *This article reports experimental investigation results of the stress relaxation in copper bolted busbar assemblies with new design concept of the bolt holes (S-design and G-design). The results of the new case are compared with the results of the classical case of the same assemblies and it is observed that for the new S- and G- designs the decrease in the fastening force is quite low which stands for a higher level of reliable assembly operation.*

Streszczenie. *In this place the editor of journal inserts Polish version of the abstract. Please leave three lines for this abstract. Of course Polish language Authors are requested to prepare also Polish "Streszczenie". All papers should have two sets: title, abstract, keywords - Polish and English. (**Przygotowanie artykułu do Przeglądu Elektrotechnicznego** - polski tytuł na końcu streszczenia - Polish tittle at the end).*
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Keywords: bolted busbar assemblies, experiment, stress relaxation, bolt hole design, loading sequence, regression equation.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

One of the most important concerns in the design of bolted busbar assemblies is the initial contact force. Considerable effort is required to provide the right holes geometry and the right penetration, and to select an alloy with the necessary strength and adequate formability. But these initial efforts must not be the only concern because some metals lose a significant amount of their initial contact force over time. This force decay is a natural consequence of the structure of all metals and is called stress relaxation.

Stress relaxation is the time dependent decrease of the stress in a metal under constant strain, such as in a busbar with fixed deflection.

Pure copper has poor stress relaxation resistance. Adding different elements to copper produces alloys with different combinations of strength, conductivity, formability- and stress relaxation resistance. All of the copper alloys are susceptible to stress relaxation, just as are all other metals. But there is a tremendous difference in the stress relaxation between different copper alloys, so alloy selection can be important. In the strictest sense, stress relaxation always occurs, over time, in any stressed member of a bolted busbar connection. But in a practical sense, some applications will experience very small losses of contact force. For highly resistant alloys, under moderate stress for short times, without exposure to high temperatures, the decrease in contact force will be within the experimental error of pre-production testing.

By understanding the variables that affect stress relaxation the designer can make choices which optimize the behavior of a contact during its expected life. Once the metal (or alloy) choice has been made, there are two other important variables that affect stress relaxation: time and temperature. And there are three variables that have less of an impact: initial stress, orientation, and the degree of cold work. The latter is expressed as temper, a traditional designation which reflects the cold reduction by rolling in cold rolled alloys, or the mechanical properties in the case of certain heat-treated alloys.

Although time and temperature are usually determined by the expected application of a bolted busbar assembly, with a suitable choice of contact metal (alloy) the loss of contact force over design life can be curtailed. By management of three secondary variables, the loss of contact force over time can be further reduced. The secondary variables are: initial stress level, orientation, and temper.

The rate of stress relaxation is influenced by the initial stress. If the busbar is initially deformed such that it is stressed at its yield strength, then rapid loss of contact force may occur. If the stress is only 20% of the yield strength, practically no loss occurs. Initial contact forces are such that applied stresses are commonly 30-90% of the metal's yield strength, and within that range the loss of contact force is almost invariant with S_i. That is why stress relaxation testing is usually done with initial stress levels of 75% of the metal yield strength.

Although stress relaxation continues over long periods of time, the rate is highest initially and decreases with increasing time. This makes it convenient to plot the data with time on a logarithmic scale against the percent remaining stress, as shown in the figure below for cartridge brass. At a test temperature of 75°C, a little over half the initial stress remains so almost half the contact force has been lost.

Stress relaxation is a function not only of metal or alloy, but also of temperature, orientation, initial stress, and, of course, time. To prevent circuit integrity from being compromised over the design life of bolted busbar assembly the loss of contact force due to stress relaxation must be taken into account. When should the designer be concerned? Not only during metal or alloy selection because, as previously noted, there are significant differences among the design of holes used for connectors, [1, 2].

There have been proposed 3 new bolt hole design cases of high power bolted busbar connections in [1] – *S-design* with slotted bolt holes, *SH-design* with slotted bolt holes, ending with small holes, and *G-design* where groups of small holes are situated around the bolt holes, as shown in Figure 1.

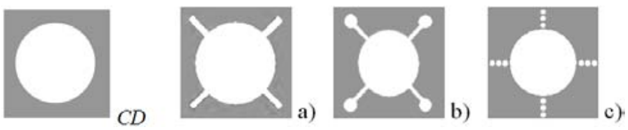

Fig. 1 Classical (CD) and new designs for bolted busbar assemblies: a) S-design; b) SH-design; c) G-design

The finite element simulation tool ANSYS Workbench is used to study the mechanical changes, associated with the contact pressure and depth of penetration in the contact area between two busbars in a bolted busbar connection.

A higher contact penetration increases both the numbers and dimensions of α-spots. This in turn expands the true contact area and decreases the contact resistance, which is a precondition for introducing a new hole-shape design for this connection. Moreover, there is a significant rise in the contact penetration and pressure in comparison with the classic design case.

Figure 2 shows the G-design contact penetration status. This design comprises 4 groups (two horizontal and two vertical) of 3 small holes of diameter Ø 0.9 mm set apart at distance of 0.1mm.

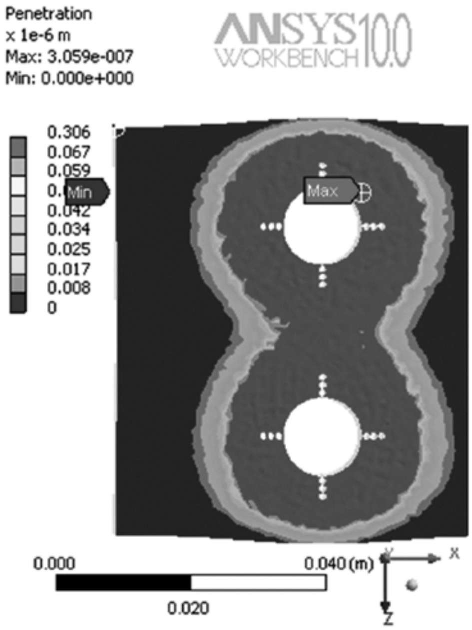

Fig. 2 G-design contact penetration

Contact resistance experimental investigation of slotted (S-design) and perforated (G-design) of bolted busbar connections is given in [2].

The newly incorporated design concepts with slots and groups of small holes have proven to exert substantial influence on the contact resistance of bolted busbar connections. All of the investigated S- and G-designs reveal a decrease in the contact resistance values as opposed to the classic case. The major decrease is approximately 50%. Figure 3 shows the classic case (RC) and the G-design (RG) contact resistances of the copper connections as a function of time (for 1 hour period). This result will lead to a more reliable behavior of the newly proposed contact assemblies.

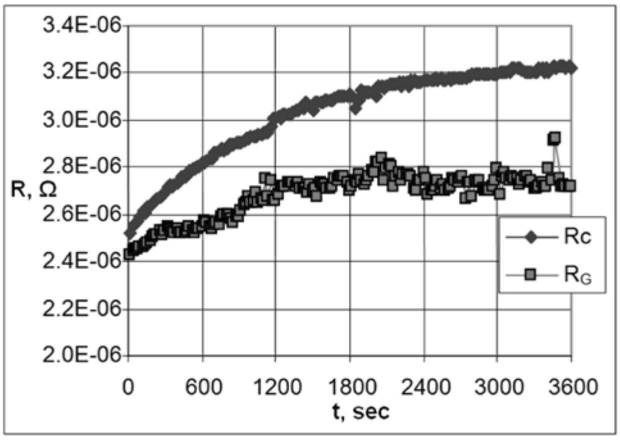

Fig. 3 Contact resistances, R_C of the classical and R_G of the G-design case copper connections as a function of time (for 1 hour)

Knowledge of the problems dealing with stress relaxation and creep in contact assemblies is of vital importance for the reliable operation.

Stability of dislocation structures in copper towards stress relaxation, investigated by high angular resolution 3D X-ray diffraction, is given in [3]. Structural dynamics is experimentally analyzed on a sample of 99.99% pure copper material.

Creep-Fatigue Deformation Behaviour of OFHC-Copper and CuCrZr Alloy with Different Heat Treatments with and without Neutron Irradiation are presented in [4]. The essential conclusion of this work is that the application of holdtime generally reduces the number of cycles to failure. The largest reduction has been found to be in the case of OFHC-copper. The reduction in the yield strength due to overaging heat treatments causes a substantial decrease in the number of cycles to failure at all of the investigated holdtimes.

In [5] stress relaxation and creep are investigated in electrodeposited and rolled copper foils, 12-35 µm thick, near yield stress, at room temperature. It has been established that the relaxation and creep are significantly lower for the rolled foil.

Reduction of joint force by creep in high current joints is presented in [6]. Depending on the joint temperature, the aluminum alloy and different joint-geometry types, the joint force reduction in high current aluminum joints is measured through long-term experiments. It has been shown that joint force reduction by creep may play an important role in the long-term stability of aluminum joints for electric power applications if the joints are stressed continuously by the rated current.

Theoretical and experimental results of the decrease in the joint force due to creep of the conductor material are shown in [7]. The experiments are carried out at different joint temperatures and for different joint geometries, with and without disc spring washers or retightening. The impact of stress relaxation on the long-term response of the joint resistance is also discussed.

Two technical aluminum alloys have anomalous creep behavior under certain stress and temperature conditions as shown in [8]. The phenomenon has been studied in details through alloys, characterized by global and local texture measurements, using neutron and electron backscatter diffraction.

The objective of the current study is to analyze experimentally the stress relaxation in copper bolted busbar assemblies with new design concept of the bolt holes (S- design and G- design) and compare the new and the classical busbar design case response.

Experimental investigation of stress relaxation

There are several kinds of equipment and several methods used to determine the stress relaxation of metals. An excellent reference is "ASTM E 328, Standard Methods for Stress Relaxation Tests for Materials and Structures", published by the American Society for Testing and Materials. Of particular note is that this standard includes bending test methods.

The data from stress relaxation tests may be treated in different ways. For example, to estimate the amount of stress relaxation for a long time, short time tests may be extrapolated rather than use tests extending over a significant percentage of design life. These techniques are based on the well known fact that the percentage remaining stress in a metal under test tends to decrease in a linear fashion when plotted against time on a logarithmic scale.

Copper busbars, measuring 160 x 60 x 10 mm, are used to study the stress relaxation within the area of mechanical loading around the fastening holes.

The bolts and nuts for fastening the busbars are substituted with equivalent force produced by cylindrical steel bodies (denting bodies of steel St45) with ∅ =10 mm. The contact area, thus created with the copper busbars is identical to that produced by M10 bolts and nuts. It is assumed that the bolt is much stiffer than the cooper busbars, it has no deformation as a function of time and the stress relaxation is negligibly small and so only its effect on the stress relaxation in both of the copper busbars is considered.

The copper busbars stress relaxation is studied by a universal physical and mechanical testing machine Instron – 1185.

A pair of holes of diameter Ø 10.5 mm are drilled in each of the two busbars on any of the two sides of the plane of symmetry. The holes are at 15mm from each other and from the axis of symmetry. The first busbar pair is of the classic design (CD-design) and has four Ø 10.5 mm simple holes. The second pair is of the new, S-design, where the busbar holes have four slots, 3 mm long and 1 mm wide, arranged in such a way that the pairs of slots are on mutually perpendicular axes, rotated at 45 degrees about the busbar axes. The third pair, the G-design, has no slots but four groups of three Ø 0.9 mm small holes arranged in line. The distance between the small holes is 0.1 mm.

The stress relaxation study is carried under conditions that closely approximate actual operation: first, the two busbars are simultaneously pressed; second, the pressing speed conforms to the supposed speed that would arise if the real nut was screwed to the required standard force.

The testing bodies loading is accomplished at a constant speed of deformation of 0.5 mm/min until the force value reaches 12.3 kN, which is equivalent to fastening both bolts with a corresponding torque.

The deformation is fixed or remains constant after loading up to the final force thus initiating the process of residual force variation in time. The test is repeated in the same way after three months.

The residual force variation is generated as a function of time through regression analysis of experimental data. The coefficients of the corresponding logarithmic fit are evaluated. The time interval, during which the line tangent to the relaxation curve is at 135 degrees with respect to the abscissa is evaluated analytically.

Due to the impossibility of rendering the maximum loading force in any of the experimental tests, the obtained experimental data is normalized by performing the computations in relative units - $F^* = F/F_0$. This is accomplished by relating the current value of the force F measured during relaxation process to the value of the initial measured force F_0. In this case, the normalized value of the stress σ^* is equal to the normalized value of the loading force F^* - $\sigma^* = \sigma/\sigma_0 = F^*$, where σ_0 is the maximum stress at the time t_0 when the loading F_0 is removed. This approach to processing the experimental data, allows for the proper comparison and analysis of the received results.

Results and discussion

The experimental investigation of the influence that the new S- and G-design exert on the relaxation of the fastening aims at:

a) observing any differences during the relaxation processes after the first and the successive second loading (after three months) in any of the tested designs;

b) relating the relaxation response of the different designs;

The experimentally obtained results are shown in the graphs below. Figures from 4 to 6 present the effects of the second loading of the new bolted busbar designs.

It is obvious for all designs, that despite the similarity in the relaxation curves, the changes after the second loading tend to fade away for higher values of the normalized force. The general conclusion that follows is that regardless of the changes in the design of the busbar assembly, the contact joint relaxation is low and the joint becomes more reliable for the period of operation.

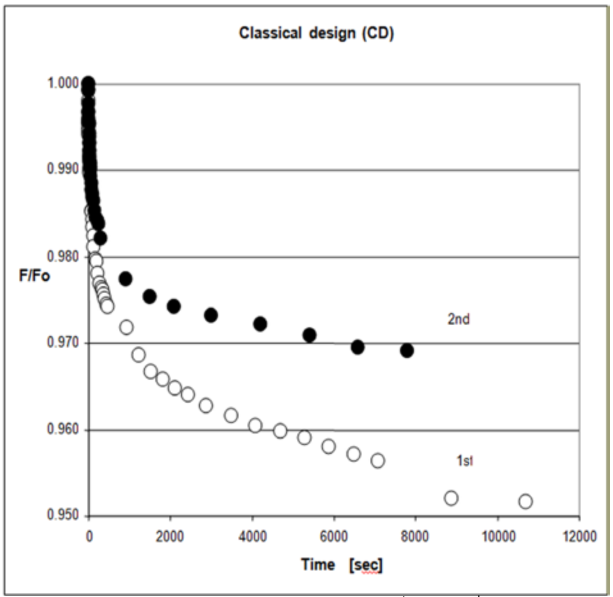

Fig. 4. Influence of the loading sequence (1st and 2nd) on the type of the relaxation curve for the case of simple hole (CD - classical design)

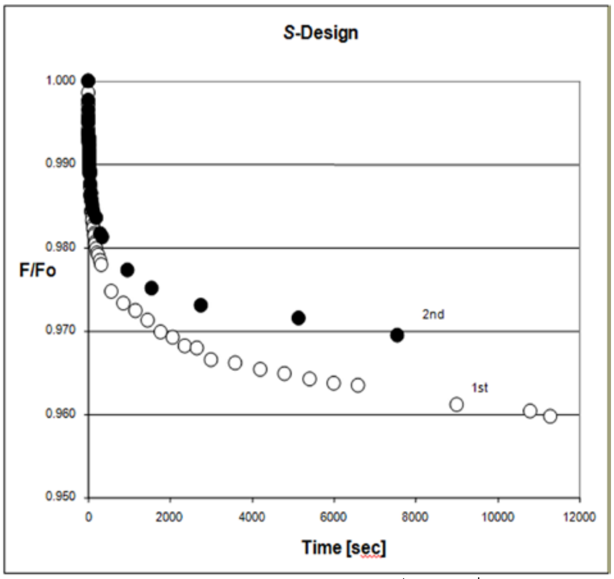

Fig. 5. Influence of the loading sequence (1st and 2nd) on the type of the relaxation curve for the case of slotted hole (S-design)

Analysis of the one month extrapolated values confirms that joints stabilization occurs for different “loss of initial elasticity stresses” (Table 1).

The minimum loss of compression (i.e. the best result of 6.1%) after the first loading of the copper busbars, is worse than the maximum value (the worst result of 5.5%) for the second series of loading. The useful information from that comparison is that a brief loading-unloading (for 5 minutes) followed by new pretension could be much beneficial to the joints stability over time.

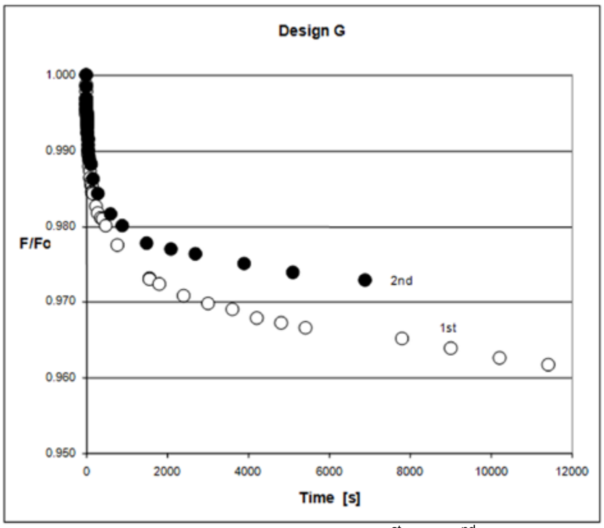

Fig. 6. Influence of the loading sequence (1st and 2nd) on the type of the relaxation curve for the case of bolt hole with groups of small holes (G-design)

The second part of this investigation has to justify the concept of complicating the design. For that purpose, the influence of different design concepts on the relaxation curves is compared for one and the same loading sequence. The results are shown in Fig 7 and 8.

Table 1. Extrapolated values for the loss of initial compression, %, after one month

Design	CD	S	G
After 1st loading	7.7	6.5	6.1
After 2nd loading	5.5	5.3	4.8

As expected, the normalized forces in the second loading converge asymptotically to higher values than the forces in the first loading. Moreover, within the region of "slower" relaxation, the three relaxation curves come closer in a narrower interval which signifies that the influence of the design sufficiently decreases.

There are also compared the time periods when force variations are time commensurate. This comparison provides information about the relaxation dynamics, i.e. the effective retention capacity of the different design cases with respect to the decrease in the compression force.

The analytically evaluated time interval, during which the line tangent to the relaxation curve reaches an angle of 135 0 with respect to the abscissa, is chosen as the criterion for this. Table 2 lists these values for each of the designs and for any of the successive loadings.

It is obvious from Table2, that the time required for reaching the specific slope is shorter for the second loading cycle.

All of the tested design concepts provide the same response. It means that the processes are much more relaxed, as a result of which the second region of the curve is reached much faster and the losses in the compression force are lower as a whole.

The assumption that the modified designs would facilitate relaxation is confirmed once more. Any further analysis proves that for real-world applications it would be better to choose the simplified, cheaper and more accessible for production busbar design with slotted holes, since the difference with the complicated concept is not significant, in case the absolute times are not considered.

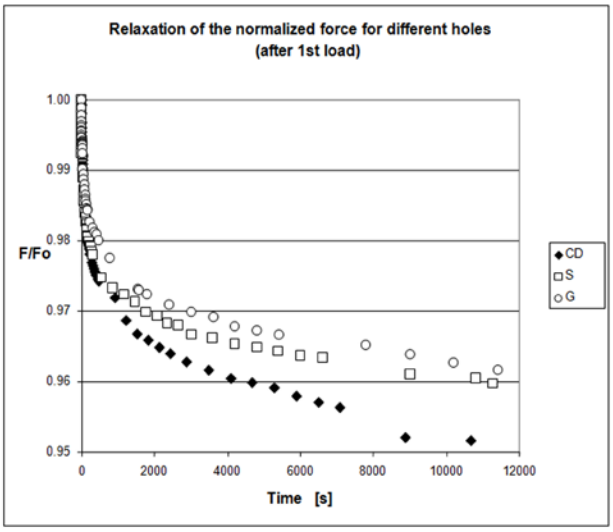

Fig. 7. Influence of the design concept (CD, S, and G) on the normalized relaxation relations after the first loading

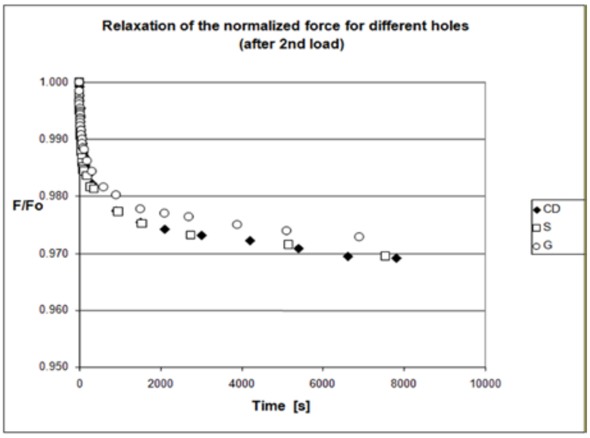

Fig. 8. Influence of the design concept (CD, S, and G) on the normalized relaxation relations after the second loading

Table 2 Time (in seconds) for the slope to reach an angle of 135 degrees or time for quick stress relaxation

Design	CD	S	G
After 1st loading	68.1	55.9	54.3
After 2nd loading	46.9	44.6	41.3

If the relaxation response of any of the design cases is traced in details, it will become evident that the corresponding design type plays a definitive role. As shown in Fig.8, the time for reaching the required loading is found to be dependent not only on the design type but also on the loading sequence.

The experimental results allow for predicting the stress relaxation response beyond the studied time range. The experimentally obtained curves F* (t) = σ* (t), shown in Fig. 4 to Fig. 8, depict stress relaxation for a short period of time ranging from 3 up to 3.5 hours. Truly, the study deals with the time of "quick" stress relaxation (max 68.1sec, Table 2), after which elastic stresses change considerably slower. However, in view point of the assembly operation, a question of interest is the relaxation response of copper after 10, 15, 20 years. Our experiments proved that the normalized (relative) stress σ* (resp. force F*) and the natural logarithm of the time ln t (in seconds) are related linearly as follows:

(1) $$\sigma^* = \sigma / \sigma_0 = 1 - B.\ln(t)$$

Table 3 lists the regression equations as well as the corresponding correlation coefficients (R^2) for the studied design cases of the bolted busbars for two successive loadings at intervals of three months. The same relations are shown in Fig.9 and Fig.10, separately for both loadings which facilitates the tracing of the positive effect of introducing the new design.

The slope of the straight line σ* (ln t) could be used as an integral feature of the stress relaxation process – the lower its value, the slower the process, which provides for the better operating parameters of the bolted busbar connection. If the slope of the fit line for the classical case (CD) is taken as a reference, then the rate of lowering the slope, when the new designs (SH and G) are introduced, reveals the positive effect of decreasing the stress relaxation speed B and retaining the contact force F* (respectively the elastic stresses σ*) in the copper.

Table 3 Stress relaxation equations for CD-, SH- and G-design of bolted busbar assemblies

Design	Regression Equation	Correlation Coefficient R^2
First Loading		
CD - design	σ* = F* = 1 - 0,005459 ln(t)	0.9995
SH - design	σ* = F* = 1- 0,004491 ln(t)	0.9987
G - design	σ* = F* = 1 - 0,004381 ln(t)	0.9990
Second Loading		
CD - design	σ* = F* = 1 - 0,003816 ln(t)	0.9877
SH - design	σ* = F* = 1 - 0,003620 ln(t)	0.9916
G - design	σ* = F* = 1 - 0,003354 ln(t)	0.9859

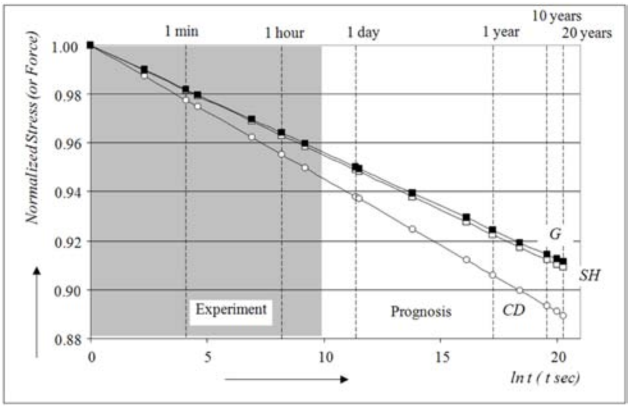

Fig. 9. Normalized stress relaxation of the design concept CD, S and G after the first loading

The stress relaxation speed B decreases as follows:

- first loading – 23% for SH-design; 20 % for G-design;

- second loading (after 3 months)– 30% for CD-design; 34 % for SH-design; 39 % for G-design;

The advantage of the second loading is evident. The loading comprises loading-relaxation cycle (for approx. 3 hours) – unloading and again, after 3 months, the same loading-relaxation cycle is repeated, Fig.9 and Fig.10. After 10 years of operation of the copper bolted busbar connection under the first loading, none of the studied designs have indicated normalized stresses, resp. forces, above 0.92. After 20 years of operation under the second loading, the normalized stresses, resp. forces, remain above 0.92 for all of the designs.

The G-design is presumably the best that fulfils the operating requirements for the bolted busbar connection, i.e. its elastic stresses decrease at the slowest rate during relaxation.

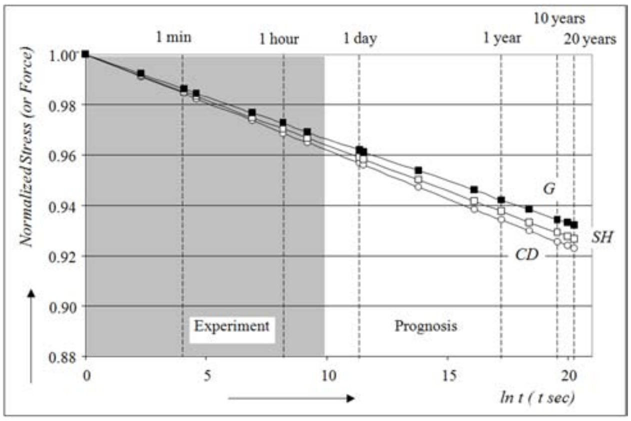

Fig. 10. Normalized stress relaxation of the design concept CD, S, and G after the second loading

Solving equation 1 with respect to time yields equation 2

$$t_n = \exp\left(\left(1-\sigma_n^*\right)/B\right) \quad (2)$$

where: t_n - time after which the normalized stress, due to relaxation, attains the predetermined value σ_n^*

The time tn for attaining, during relaxation, to $\sigma_n^* = 0.94$ (94% of the initial stress σ_0) could be determined and the results are shown in Table4.

Table 4 Time required for attaining, as a result of relaxation, to the stress relaxation equations in the case of CD-, SH- and G-design of bolted busbar assemblies

Bolted Busbar Assembly Design	CD-design	SH-design	G-design
First Loading	17 hours	176 hours (7.34 days)	246 hours (10.26 days)
Second Loading	1872 hours 78 (days)	4 385 hours (183 days)	16324 hours (680 days)

The reported results for the relaxation response of the studied bolted busbar assemblies (CD, SH and G design) outline even clearer the different design effectiveness. Differences are essential and allow for selecting the proper structural design, Table 4.

The histogram shown reveals an interesting fact. In spite of the increasing deformation required for reaching the necessary force, the relaxation process runs faster and the loss of compression force is lower.

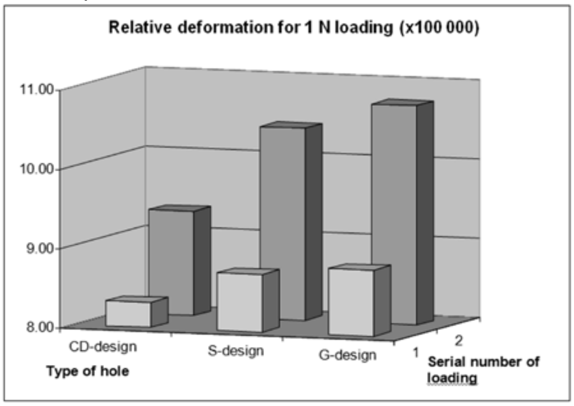

Fig. 11. Relative deformation (x 100 000) for initiating a force of 1N for the different hole designs when a different loading sequence is followed

Furthermore, the same figure clearly outlines the design influence. There is an evident increase in the deformation in the slotted hole case, especially for the second loading cycle. It is logical to assume that due to the facilitated deformation around the bolt hole, there could be quite significant changes going on in the material structure. It becomes a precondition for the accelerated rate of the relaxation processes – already shown by the Table 2 data.

Conclusions

The dependencies outlined up to here allow for the formulation of the following more important conclusions:

1. The changes in the relaxation processes have been studied for copper bolted busbar assemblies with new design concepts of the bolt holes. It has been observed that design complications (S- and G-design) bring advantages in relation to the rate of stress relaxation and loss of compression force in the joints which is directly related to the joints level of reliability during operation. The G-design is reported as the concept with better relaxation response.

2. The two new design cases (S- and G-design), despite the similar relaxation response, tend to have their second loading cycles relax faster in the starting part of the curve (faster stress relaxation). The trend appears for a higher value of the residual elastic stresses within the operating part of the relaxation curve.

3. By changing the design of the bolted busbar assembly, the relaxation response of the assembly could be controlled in such a way as to allow for higher elastic stresses and higher level of reliability.

REFERENCES

[1] R. Tzeneva, Y. Slavtchev and V. Mladenov, New Connection Design of High Power Bolted Busbar Connections, *The Proceedings of the 11-th WSEAS International Multiconference CSCC (Circuits, Systems, Communications, Computers)*, (Volume 1), (2007), 227-232.

[2] R. Tzeneva, Y. Slavtchev, N. Mastorakis, and V. Mladenov, Experimental Investigation of Contact Resistance of Slotted and Perforated Bolted Busbar Connections, *Proceedings of the 12th WSEAS International Conference on Circuits*, (2008), 142-146.

[3] Bo Jakobsen a.o., Stability of dislocation structures in copper towards stress relaxation investigated by high angular resolution 3D X-ray diffraction, Phys. Status Solidi A206, No. 1, (2009), 21–30

[4] B.N. Singh, M. Li, J.F. Stubbins and B.S. Johansen, Creep-Fatigue Deformation Behaviour of OFHC-Copper and CuCrZr Alloy with Different Heat Treatments and with and without Neutron Irradiation, Riso National Laboratory, Roskilde Denmark, (2005)

[5] Merchant H.D., Stress relaxation and creep of 12 to 35µm copper foil, *Journal of electronic materials*, Vol. 26, No.7,(1997)

[6] S. Schoft, J. Kindersberger, H. Löbl, Reduction of Joint Force by Creep in High Current Joints, *Proceedings of the 21th Conference on Electrical Contacts* (2002), Zurich, 406 – 412

[7] Schoft S., Measurement and calculation of the decreasing joint force in high current aluminum joints, *Proceedings of the 22nd Conference on Electrical Contacts* (2004), Seattle, 511 – 518

[8] Oertel C.-G. a.o., Anomalous creep behaviour of aluminium high current joint materials, Cryst. Res. Technol. 40, No. 1/2, (2005), 83 – 89

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