Maintain Bolt Preload on Electrical Connections Using Belleville Springs

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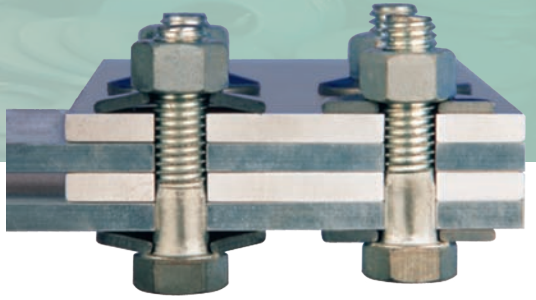


Keep Connections “Tight” after Differential Thermal Expansion

Belleville springs are commonly used on electrical connections. Electrical connections are often made up of materials that have various coefficients of thermal expansion. In addition, the joint materials also carry more current than the bolts. This causes the joint to heat up more than the bolts. The resultant differential thermal expansion (DTE) results in an increase in bolt load, possible causing the joint material to yield.

This yielding of the material causes a decrease in load holding the joint together which in turn increases the electrical resistance during the next thermal cycle. Eventually enough heat may be generated to result in what is referred to as a “hot spot.”

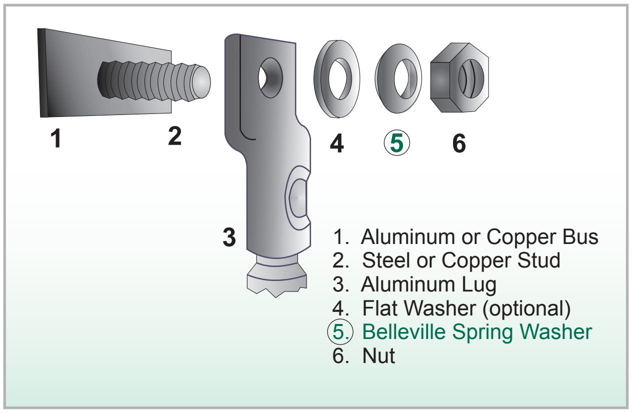
“Hot spots” are produced at bolted electrical joints when there is more heat generated by current passing through the joint than can be effectively dissipated. This can result in catastrophic failure of the joint. Belleville springs counteract the effects of differential thermal expansion by maintaining sufficient load on bolted electrical connections to prevent "hot spots" during and after temperature cycles.

A bolted joint without a Belleville spring relies on the bolt stretch to produce the load at the contact joint. Bolt stretch produces small amounts of movement at very high spring rates. Creep of the material making up the joint can cause significant loss of load at the joint with little movement of the material.

A Belleville spring’s deflection to flat is seven to ten times the stretch of a bolt for the same load. The combined deflection of the Belleville spring and the stretch of the bolt produce a much lower spring rate for the same load on the contact joint. Thus, for the same creep of the joint material, there is little loss of load at the contact joint. After the initial loss of load due to creep and relaxation, the Belleville spring acts as a shock absorber and stabilizer by maintaining a constant sufficient load on the bolted joint.

The most common materials used for Solon Belleville Springs® in this application are 301 Stainless Steel, 17-7PH Stainless Steel, 6150 Alloy Steel, 1074 Carbon Steel, 718 Inconel and 510 Phosphor Bronze. The 6150 and 1074 materials are available with a mechanical zinc plating to resist corrosion.

Installation procedures should follow manufactures recommendations with regard to tightening methods and lubrication. There are no industry standards for bolt size / bolt load. Recommended bolt loads or torques should be obtained from either the connector manufacturer or the utility directly.



Typical Electrical Assembly

Analysis Using Belleville Springs on Electrical Connections

The following assumptions will be made for this analysis:

1. The bus bar will be fabricated from two 1/4" thick sections of EC-H13 aluminum.
2. For the first analysis (where no springs are used), the fastening system will consist of a 1/2" stainless steel bolt and two 1/8" thick stainless flat washers. In the second case, two 1/8" thick stainless Belleville springs will be used along with the flat washers. The flat load of the springs will be 7,100 lbs.
3. The temperature at assembly will be 70°F. With the conductor in service the bus temperature in the vicinity of the bolt will reach 220°F. Since the bolt carries no current, its temperature will only reach 150°F.
4. For simplicity, the assembly preload will be equal to the flat load of the Belleville spring, 7,100 lbs.

If the loading plane is the joint interface between the Belleville spring face and the bus bar, the diagram would look like the one shown in Figure 1a[1]. On the left side is the joint with a deflection of dT at load Fp, while the right side is the bolt with stretch dL at Fp. The dashed line represents the continuation of the elastic curves for the bolt and the joint at higher loads. Note that the elastic curve for the joint begins to “flatten out” above Fp. This is because the soft joint material yields at relatively low levels of stress. The drawing to the right of the joint diagram shows a load (Lx) that is applied at the loading plane. As Lx is increased, the joint is unloaded while the bolt is loaded. In other words, Lx will reduce joint deflection and increase bolt stretch.

Now, for a bus conductor connection, the load at the joint interface of the two sections of the bus bar is of greatest interest. This load is directly related to the contact resistance (and efficiency) of the joint. Therefore, the loading plane used for this analysis will be shifted to the center of the joint (see Figure 1b). There will no longer be two “sides” to the joint diagram. This is because any load Lx will increase load on both the joint and the bolt. Since Lx increases bolt stretch and joint deflection, these values should be on the same side of the joint diagram. When the preload Fp is applied, the horizontal leg of the diagram will equal the sum of the deflection in the joint and the stretch in the bolt = dT + dL.

For this example, the assembly preload is 7,100 lbs. Since the joint had hardly yielded at this point, the diagram is basically a right triangle. At this preload, the deflection of the joint is .0052" and the bolt stretch is .0017". Therefore, the horizontal leg of the triangle is .0052" + .0017" = .0069".

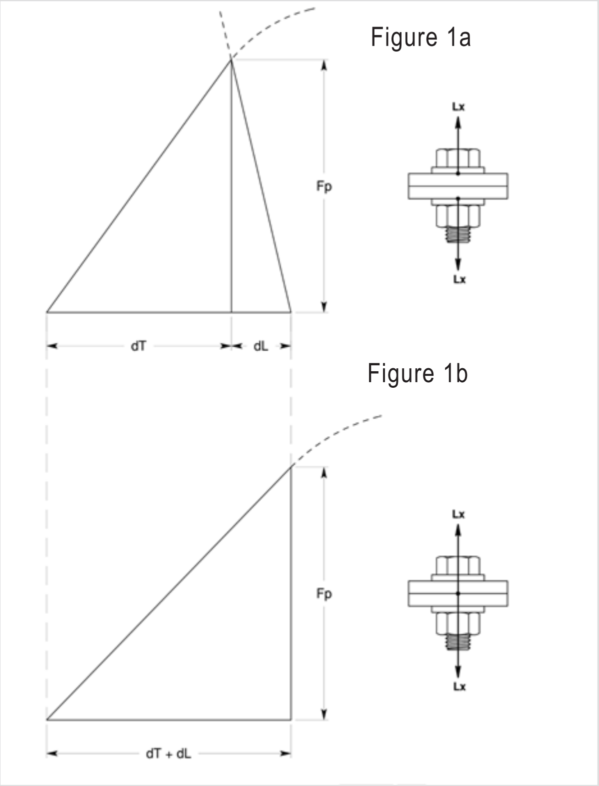


Figure 1a and 1b
Shows joint diagram with different loading plane positions. When the loading plane is moved to the center of the joint, the diagram has only one side because a change in Lx has the same effect on all of the joint components. In other words, as Lx increases, the bolt, joint, flat washers, and Belleville springs are loaded.

As stated earlier, when current begins to run through the conductor, the assembly begins to heat up. Using the assumed service temperatures and material properties, the change in lengths ΔL of the bolt, joint, and flat washers can be determined using the following equations:

$$\Delta L_B = \rho_B * L_B * \Delta T_1$$
$$\Delta L_J = \rho_J * L_J * \Delta T_2$$
$$\Delta L_W = \rho_W * L_W * \Delta T_1$$

where, ρ_B = coefficient of thermal expansion of the bolt material
= 6.4×10^{-6} in/in/F
ρ_J = coefficient of thermal expansion of the joint material
= 12.8×10^{-6} in/in/F
ρ_W = coefficient of thermal expansion of the washer material
= 6.4×10^{-6} in/in/F
L_B = grip length of the bolt = 1.25 in.
L_J = thickness of the joint = 1.00 in.
L_W = thickness of the washer = .125 in.
ΔT_1 = change in temperature of bolt and washer = 150˚F - 70˚F
ΔT_2 = change in temperature of joint = 220˚F - 70˚F

therefore, $\Delta L_B = 0.0006$ in.
$\Delta L_J = 0.0019$ in.
$\Delta L_W = 0.00005$ in.

Note that the joint expands more than the bolt does. This will cause an increase in preload. The change in load caused by the differential thermal expansion F_T can be found using the following equation[1] [see reference 1]:

$$F_T = \frac{K_B * K_J}{K_B + K_J} * (\Delta L_J + 2 * \Delta L_W - \Delta L_B)$$

where K_B and K_J are the spring rates of the bolt and the joint, respectively[2]. Using the figures for the spring rates and expansions calculated earlier, the increase in preload F_T is 1,425 lbs. This increase is reflected on the joint diagram in Figure 2. Remember that the elastic curve is non-linear above the preload because the joint begins to yield at 7,000 lbs.

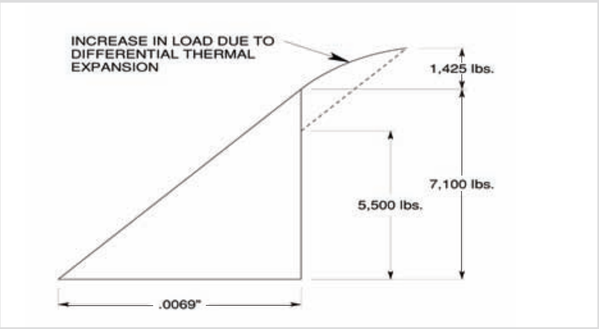


Figure 2
Joint diagram showing the yielding of aluminum as load is increased by 1,425 lbs. due to differential thermal expansion. The dashed line reveals that preload will fall to 5,500 lbs as temperature returns to 70°F.

When the temperature returns to 70°F, the residual preload will be lower than at assembly (represented by dashed line in joint diagram). Note that the load on decrease is parallel to the linear portion of the elastic curve. This is because yielding in the bus bar material had effectively shifted the joint diagram. For this example, an increase of 1,425 lbs. will result in a yield of 0.0015". A 0.0015" shift will cause residual preload to fall to 5,550 lbs. (a 22% decrease). Since the lower preload will increase contact resistance, as current runs through the conductor more heat will be generated. This will not only increase the differential thermal expansion, but may also cause the joint material to unload even more due to creep. Each time the bus conductor is cycled more load will be lost until the connection eventually fails.

Now consider the case where Belleville springs are used. Assume that two springs in series with .019" of deflection (h) are used. The load applied to the bolt is the same as when no springs were used. Therefore, the vertical leg of the joint diagram in Figure 3 (page 4) is the same (7,100 lbs.). However, the two Belleville springs have added 2 X .019 " = .038" to the horizontal leg. This decreases the slope of the elastic curve by a factor of 6.5. Since their materials and thicknesses are the same, the change in length of the Belleville springs will be the same as the flat washers (.00005"). Now, the change in load can be computed:

$$F_T = \frac{K_B * K_J}{K_B + K_J} * (\Delta L_J + 4 * \Delta L_W - \Delta L_B)$$

Note that this formula is virtually the same as the one used for no Belleville springs. The only differences are that the change in length of the Belleville spring is multiplied by four rather than two and the bolt length is 1/4" longer. This accounts for the two Belleville springs. The spring rates of the Belleville springs are not in the equation because they are in the flat position when the preload is 7,100 lbs. Plugging in all of the numbers yields an increase in preload F_T of 1,347 lbs. The increase in load is shown by the solid line on the joint diagram in Figure 4 (page 4). Note that when load is raised above 7,100 lbs., the slope of the elastic curve increases. This is because the springs will no longer deflect beyond their flat load. The joint material will yield as if there were no Belleville springs. However, as the components return to their original temperature, preload falls quickly until the flat load of the springs is reached. Then the Belleville springs begin to unflatten slightly to “absorb” some of the change in load. This is why the unloading line changes slope (see the dashed line in Figure 4) at the flat load of the springs. For this example, the differential thermal expansion resulted in only a 3.4% decrease in preload. This a substantial improvement over the 22% lost when no springs were used.

$$F_T = \frac{K_S * K_B * K_J}{K_J * K_S + K_S * K_B + K_B * K_J} * (\Delta L_J + 2 * \Delta L_W - \Delta L_B)$$

The next time the bus conductor is cycled, the increase in preload will be much smaller. Because the Belleville springs are no longer flat, their spring rate can be incorporated into the formula for change of load due to differential thermal expansion:

where K_S is the spring rate of two Belleville springs. In this case, the differential thermal expansion will cause an increase of 237 lbs. Such a small increase in preload should not lead to any yielding of the bus joint. Therefore, when the assembly cools to ambient, preload will return to the same level. This is why many plant procedures call for the technician to tighten the bolt until the Belleville springs become flat, and then “back-off” 1/4 turn. Backing off allows the spring to unflatten by a small amount so that any differential thermal expansion will be “absorbed” by the Belleville spring. The example reveals that this practice is unnecessary. After a single thermal cycle, the spring unflattens slightly anyway.

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[1] *Joint deflection was determined empirically while bolt stretch was calculated using Hooke’s Law. The yield point of the bus bar was found through testing to be 7,000 lbs.*

[1] *This equation is based on a linear elastic curve. Actual increase in load may be slightly less because of yielding of the joint. On the other hand, loads may be increased since the yielding will cause temperature (and differential thermal expansion) to increase. Each of these phenomena should offset each other which would lead to fairly accurate results.*

[2] *The spring rate of a flat washer is negligible.*

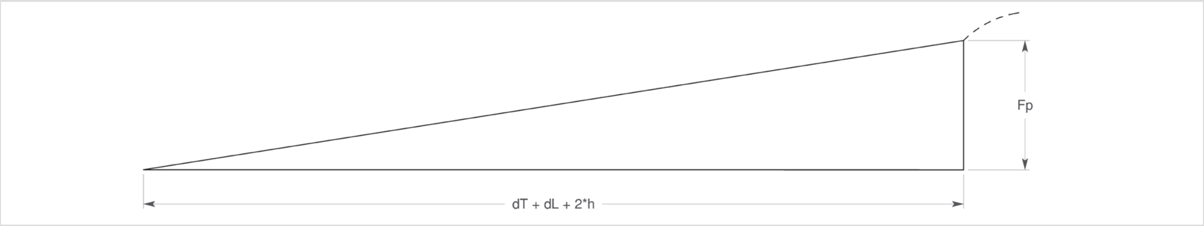

Figure 3
Shows the joint diagram using two Belleville Springs with the loading plane at the center of the joint. Note the elastic curve changes slope (dashed line) if load is increased beyond 7,100 lbs. This is because the springs are flat at this point.

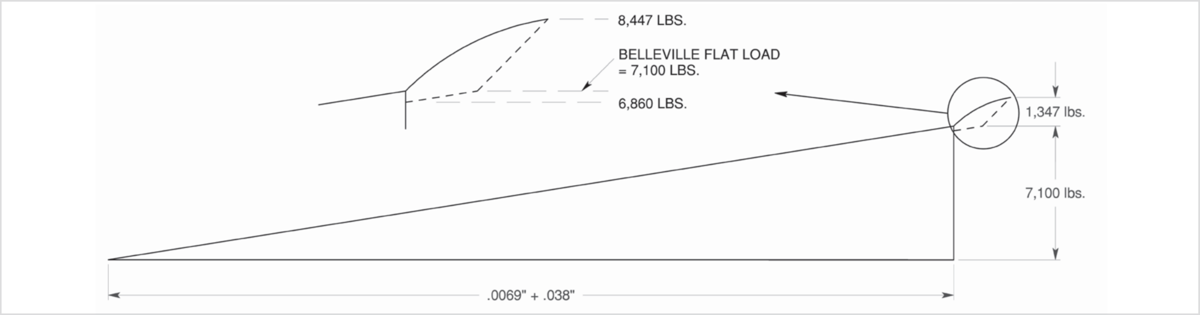

Figure 4
With Belleville springs, the differential thermal expansion causes a 1,347 lb. increase in load. However, when temperature returns to 70°F, the joint unloads (along the dashed line) at a steep rate until the flat load of the springs is reached. Then the Belleville springs begin to “absorb” some of the change in the load so that residual preload only falls to 6,860 lbs.

George Davet, BSME, is vice president and chief engineer for Solon Manufacturing Co. Mr. Davet has written and published numerous articles on the application of Belleville springs. He can be reached at gdavet@solonmfg.com.

References

1. Bickford, J., “An Introduction to the Design and Behavior of Bolted Joints,” Marcel Decker, Inc., New York, 1995.

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