Analysis of the torsional load capacity of V-section band clamps

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Abstract. This paper investigates the torsional load capacity of three sizes of V-section band clamps when assembled onto rigid flanges by comparing experimental data with a developed theoretical model. This mode of failure is of particular interest for turbocharger applications where, in use, they are subjected to torsional loading via thermal and vibrational effects. The theoretical model developed allows the impact on torsional load capacity of a number of joint parameters to be investigated and good correlation of the results, incorporating variations in coefficients of friction and dimensions, has been shown for the two larger band sizes. For smaller diameter bands, the experimental data suggests that as the band is tightened, contact with the flange is localised rather than being over the full circumference of the band. The coefficients of friction, in particular that between the flanges, and the position of the contact point between band and flange have been shown to have a significant impact on the theoretical torsional load capacity of V-section band clamps.

Introduction

V-section band clamps are a derivative of Marman clamps; used for a wide range of applications, particularly in the automotive and aerospace industries. Previous work on the Marman clamp systems includes satellite separation shock [1] and dynamic behaviour [1, 2] of such clamps on spacecraft. The sealing performance [3] of V-insert clamps used on exhaust pipes has also been studied.

The V-section band clamps considered in this paper are made from a solid, flat-bottomed, V-section ring with associated trunnion loops and t-bolt fastening, Fig. 1 [4], which are the more common type used in turbocharger assemblies.

Fig. 1 V-section band clamp assembled onto a pair of stiff flanges

A theoretical model of the internal loads in V-band joints was presented in [5] extended to include axial clamping load in [6]. More recently, preliminary studies have been reported on ultimate axial load capacity [7]. However, little work has been done to analyse the torsional load capacity of such joints; a mode of failure of particular interest in turbocharger applications. A small study has been reported [8], whereby the axial clamping load predicted in [6] was used in place of the thrust load within a clutch theory based approach to predict the torsional load capacity of V-band joints. However, the transverse friction effect reported in [6] and [9] as being significant was disregarded.

This paper will investigate the torsional load capacity of three sizes of V-section band clamps when assembled onto rigid flanges. The theoretical model developed will be based on the infinitesimal segment previously used in [6] rather than considering the V-band as a whole. The impact on torsional load capacity of a number of joint parameters including t-bolt tension, friction and the position of the contact point between band and flange will also be investigated.

Theoretical approach

The full torsion model (T_{TOTAL}, total theoretical torque capacity) is made up of two parts, torque at the flange-to-flange interface (T_F) and torque at the flange-to-band interface (T_B). The first part, T_F, is calculated using single plate clutch theory, assuming a uniform pressure distribution [10]. This part of the theoretical development is similar to that presented in [8]. The transmitted torque at the flange-to-flange interface, T_F, using the definition of F_A in terms of t-bolt load, F_β, which is given in [6] is:

$$T_F = \frac{2}{3}\mu_F\left(\frac{r_o^3-r_i^3}{r_o^2-r_i^2}\right)\frac{(1-\mu_B\tan\phi)F_\beta(\sin\phi+\mu_B\cos\phi)}{\mu_B(\tan\phi+\mu_B)}\left[1-\exp^{\left(\frac{-\mu_B\beta}{(\mu_B\cos\phi+\sin\phi)}\right)}\right] \tag{1}$$

Where r_o and r_i are the outer and inner radii of the flange contact faces, ϕ is half the included angle of the V-band section and β is half the arc angle of the band.

In order to determine the torque capacity, T_B, of the interface between the band and the flange the theory presented in [6] is extended. Within the V-band joint, tightening the t-bolt will generate a normal force per unit length, q, between the band and the flange, which is related to the radial force per unit length, f_r, and the static coefficient of friction at the band to flange interface, μ_B. Then, using the relationship between f_r and the circumferential force F_θ generated in the band by tightening the t-bolt yields:

$$q = \frac{F_\theta}{2(\sin\phi+\mu_B\cos\phi)R} \tag{2}$$

Considering an infinitesimal annular segment $d\theta$ of the band, the torque reaction between the band and one flange, dT_B, is given as

$$dT_B = \frac{F_\theta\mu_B R d\theta}{2(\sin\phi+\mu_B\cos\phi)} \tag{3}$$

where $Rd\theta$ is the unit length over which the load q is acting and R is the radius of the torque.

Using the relationship in [6] between F_θ and the t-bolt load, F_β and integrating dT_B to give the total torque reaction between the band and one flange, T_B, yields:

$$T_B = 2\int_0^\beta dT_B = 2\frac{\mu_B R F_\beta}{2(\sin\phi+\mu_B\cos\phi)}\int_0^\beta e^{\left[\frac{\mu_B(\theta-\beta)}{\mu_B\cos\phi+\sin\phi}\right]}d\theta = RF_\beta\left[1-e^{\left(\frac{-\mu_B\beta}{\mu_B\cos\phi+\sin\phi}\right)}\right] \tag{4}$$

The total theoretical torque capacity, T_{TOTAL} is achieved by addition of the torque at the flange-to-flange interface (T_F), Eq. 1, and torque at the flange-to-band interface (T_B), Eq. 4.

Experimental work

The experimental work has been carried out on a special purpose torsional test rig, Fig. 2. The rig allows two flanges to be clamped together with a V-section band clamp on a supporting shaft. The flanges are attached to arms; one moved via a hydraulic ram (the lever arm), the other held stationary via a load cell (the fixed arm). The torsional load applied by the ram is transmitted through the band-to-flange contact area and the flange-to-flange contact face and reacted by the load cell. T-bolt load is measured using a small washer load cell between the trunnion collar and the t-bolt nut. Data was recorded using a digital oscilloscope. The oscilloscope also collected data from two LVDT probes, positioned to measure movement of the two arms. For each band a t-bolt load range of 1kN to10kN (in approximate 1kN increments) was applied, with full face dry contact between the flanges.

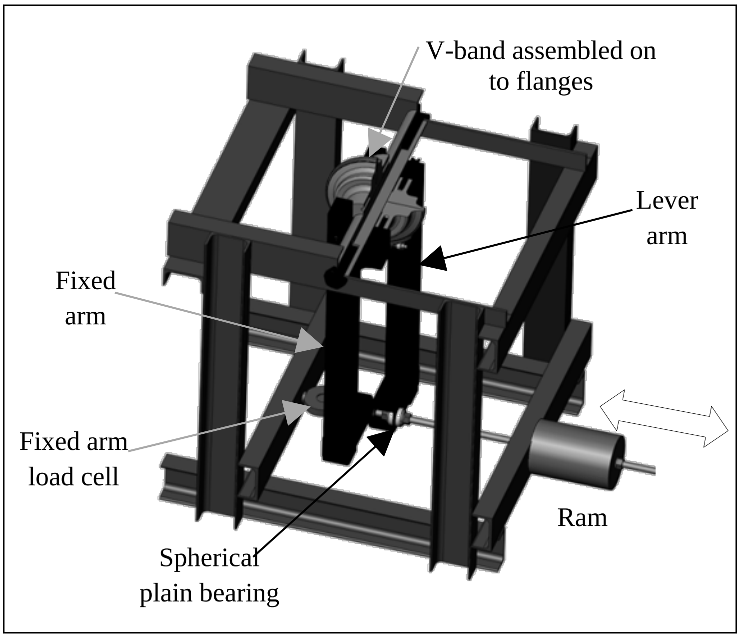

Fig. 2 V-section band clamp assembled onto a pair of rigid flanges on the torsional test frame

The point of initial torsional slip was calculated from the fixed arm load cell reading, and determined by analysing the readings from that instrument and the LVDT probe attached to the fixed arm. As joint slippage occurred, the fixed arm experienced a fast and relatively small reversal of movement as it relaxed. This slippage point was also characterised by a slight change of response from the lever arm LVDT and a small peak on the fixed arm load.

Friction

Frictional loads affect the results in three ways. As discussed in [6], increasing the friction coefficient between the band and the flanges decreases the axial clamping load generated when tightening the T-bolt. However, increasing this coefficient of friction increases the torque resistance of the band to flange joint. The final affect is between the two flange faces where an increase in coefficient of friction also increases the theoretical torque resistance. Since the band and flanges are made of different materials and by different methods, it is assumed that the coefficients of friction will be different which further complicates the effect of friction. A preliminary theoretical investigation of the effects of friction with μ varying between 0.05 and 0.5 for both band-to-flange and flange-to-flange contact areas showed that torsional load capacity could change by a factor greater than four.

Since these frictional effects can have such a large impact on the theoretical results, a practical test was carried out to assess the real coefficients of friction. This employed a standard inclined plane. The lowest and highest theoretical total torque values utilising a combination of minimum and maximum values (which are calculated as the average ± 3 standard deviations of the friction test results) are used in the comparison of theoretical results to the experimental results.

Other important parameters

Beta angle. Shoghi [5] assumed a beta angle of 167° in the calculation of applied axial clamping load, F_A. However, there is contact between flange and band of almost 180°. The stiffness of the band section and the stiffness in the circumferential direction will result in some contact pressure being generated. Using 180° instead of 167° in this theory increases the expected torsion capacity by only a small amount (i.e. approximately a 5% increase at 5kN t-bolt load).

Band diameter. The theoretical results have used the V-section band and flange specification nominal diameters. For the three sizes of band tested, varying the dimension of the inner and outer radii by ± 1 mm has a minimal effect, less than 3%, on the calculated torque capacity.

Band to flange contact angle. The parameter which has a significant effect on the theoretical results is the contact angle, ϕ, between the outer edge of the flanges and the leg of the V-section band, see Fig. 3. Nominally this angle is 20°, typically with a tolerance of ± 1°. However, this value can only be assumed if the flange edge contacts the band on the straight portion of its leg. Past researchers have generally assumed contact on the straight part of the V-section band leg. If the flange to band contact point moves to the radii between the end of the straight leg portion and the back of the band, the normal to the contact surface can be altered significantly. The position of contact point is determined by the flange tip width.

During this research the flange tip width has been investigated using a shadow graph method. However, individual band cross section geometries were not measured. Hence, the flange tip measurements have been combined with the band specification tolerance to determine maximum and minimum contact angles as shown in Table 1 for use in the theoretical calculations.

Table 1 Contact angle, ϕ

Band diameter [mm]	Minimum contact angle	Maximum contact angle
114	19°	33°
181	19°	35°
235	29°	57°

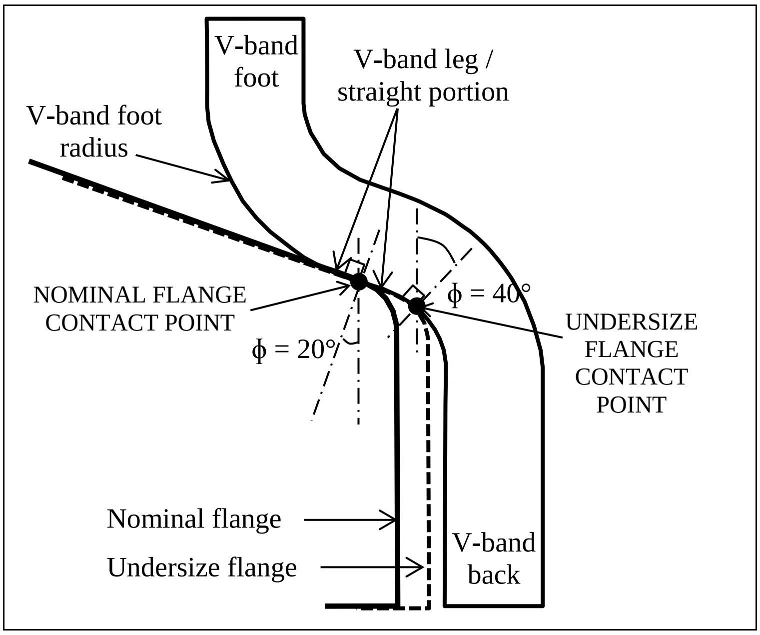

Fig. 3 Change in contact angle, ϕ, with differing flange tip widths

Results and discussion

The results are presented in Fig. 4; one graph for each V-section band diameter using the various parameters discussed above to calculate an expected range drawn from the theoretical analysis. This is compared with repeated experimental tests on the same band for each size. It can be seen that for each band size, as the test is repeated, the torsional load capacity increases.

Although reasonable correlation of experimental results to the theory is seen for the two larger diameter bands, for the smaller band the average experimental results is almost twice the average expected slip torsion. There are two plausible reasons for this. Firstly, after testing of the small band, it was noted that galling had occurred on the flange-to-flange contact area in a radial direction. This effectively increases the static coefficient of friction. Due to the localised nature of the galling marks, it was not possible to assess the influence on friction using a standard inclined plane rig. A range of coefficient of friction for the flange to flange interface of 0.55 to 0.65 would correlate well with the experimental results shown.

Secondly, it is assumed that when tightening the T-bolt, the band forms a circular arc as it comes into contact with the flanges. This assumption is reasonable for large bands where the radial stiffness is relatively low and the bands will readily conform to the circular flanges. However, smaller bands with the same cross section are much stiffer in the circumferential direction. Ensuring that these bands formed a circular arc once they were tightened to come into contact with the flanges would be extremely difficult given the manufacturing methods used (as described in [11]). Hence, it is probable that for smaller diameter bands, contact will take place over only part of the band circumference. A substantial proportion of the band tension generated by the t-bolt is absorbed by the exponentially decaying frictional circumferential reaction load. At any point on the band, this load is proportional to the contact pressure. If t-bolt tension is held constant but the contact region is reduced, the contact pressure must therefore increase. This will then lead to an increase in the torsional load capacity of the band to flange interface.

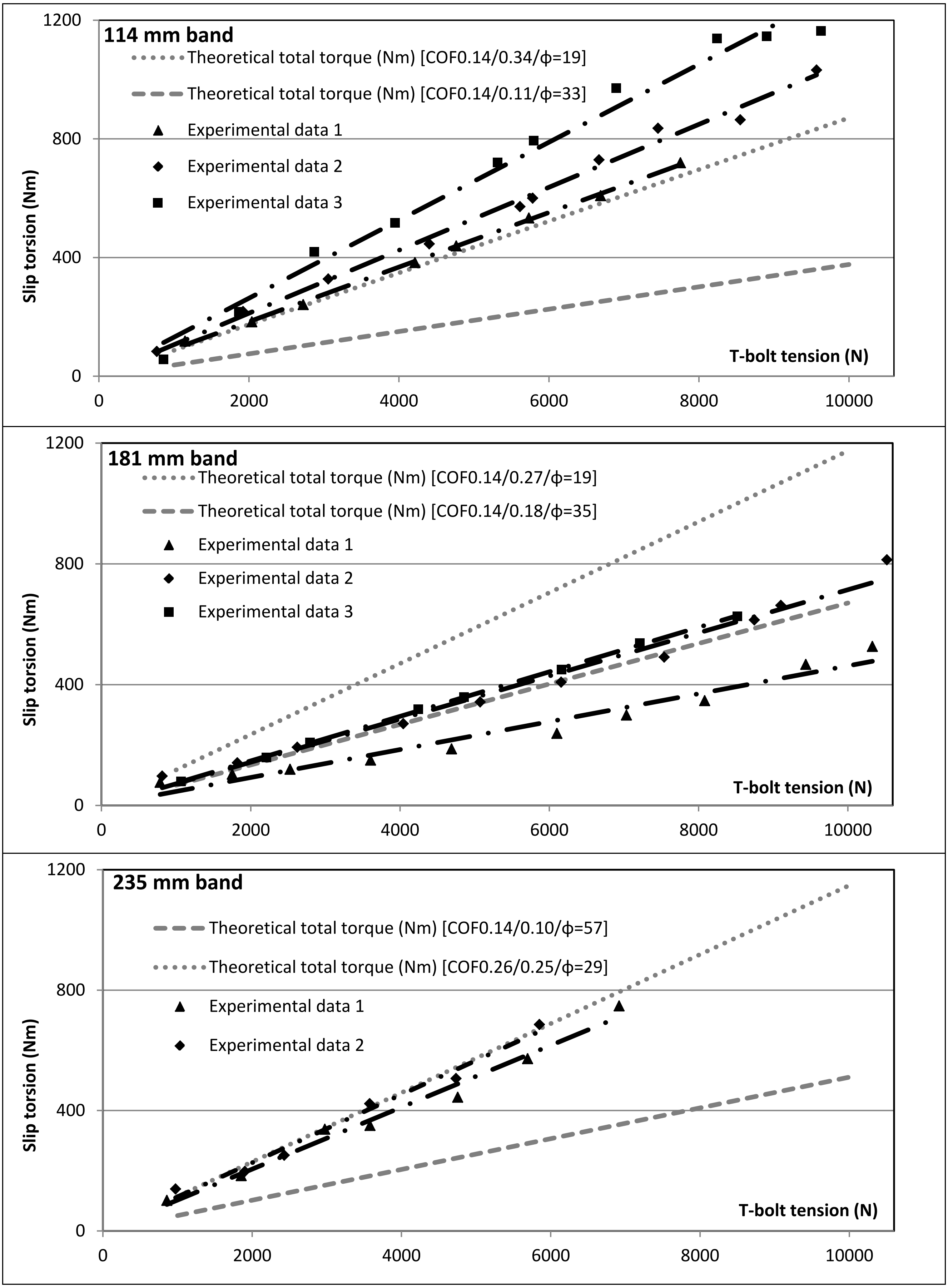

Fig. 4 Comparison of theoretical and experimental results for three band sizes

Conclusions

This paper has investigated the torsional load capacity of three sizes of V-section band clamps when assembled onto rigid flanges. The theoretical model developed has been shown to have good correlation to the experimental results for the two larger band sizes.

The coefficients of friction, in particular that between the flanges, has been shown to have a significant impact on the theoretical torsional load capacity of V-section band clamps, warranting further investigation.

The position of the contact point between band and flange and hence contact angle, ϕ, has a significant impact on the theoretical torsional load capacity.

For smaller diameter bands, the experimental data suggests that as the band is tightened, contact with the flange is localised rather than being over the full circumference of the band.

Further work

The test flanges have been machined to allow for the use of a greased washer during testing and hence eliminate flange to flange contact. Also, different washer thicknesses will facilitate the investigation of varying the flange tip widths to control the contact angle, ϕ.

The circularity of the contact line on the bands as their nominal diameter is reduced to bring them into contact with the flanges should be measured. The impact of any lack of circularity will be investigated using numerical methods.

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