EFFECT OF FLANGE GEOMETRY ON THE STRENGTH OF BOLTED JOINTS

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Introduction

The Company has been called upon to investigate numerous problems with concrete, brick and steel chimneys. In the case of steel chimneys the most common complaint by far is in connection with flange bolt failures, often accompanied by shell cracking in the vicinity of the flanges. Whilst overloading may have been the cause in some cases, more often problems have been traced to a lack-of-fit between the flanges. This paper brings together the conclusions of the studies that have been made. None of these had been designed for or failed in high cycle low stress fatigue.

The ideal flange joint

Figure 1, based on the CICIND model code for steel chimneys (Figure 9.2.1), illustrates some of the desirable features of a flanged joint.

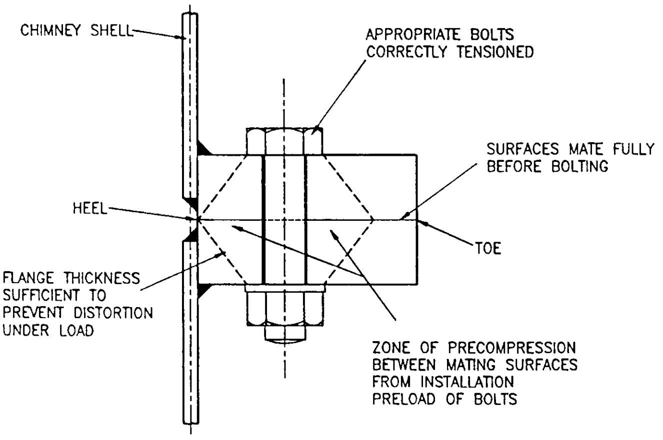

Fig. 1

The bolt force is calculated by simple statics assuming that the flanges are on the point of parting at the heel, and forming a 'fulcrum' at the toe. In fact, a properly installed nut and bolt has a pretension greater than its specified safe working load, so that, provided the flange is sufficiently rigid, wind tensions are taken mainly by relief of the precompression between the mating flange faces rather than by an increase in bolt tension. For example an M24 grade 8.8 bolt has a specified safe working tensile load of 99 kN and when installed to the recommended torque has a pretension of approximately 170 kN. Thus if the bolts are designed for safe working load the flanges will not start to part until the applied load is some 1.7 times the design value. Under such conditions the low cycle fatigue life of the bolt is not a consideration.

Types of lack-of-fit

We have encountered two common types of lack of fit which may occur separately or together. The first is where the flange is not truly normal to the shell as shown in Figure 2(a), but the heels are planar and able to mate. The second is where the flanges, whilst being normal to the shell, do not mate around the circumference as shown in Figure 2(b). The first type often occurs as a result of welding distortion which some manufacturers reduce or eliminate by adding gusset plates. The second type results from failure to match manufacture the pair of flanges forming the joint or from a subsequent change in relative orientation of match manufactured flanges, which for some reason are not planar.

In chimneys we have inspected we have discovered fabrication mismatching gaps of up to 5mm or so.

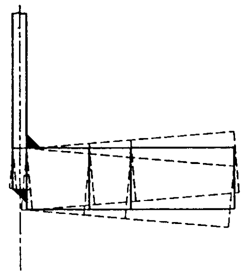

Fig. 2(a)

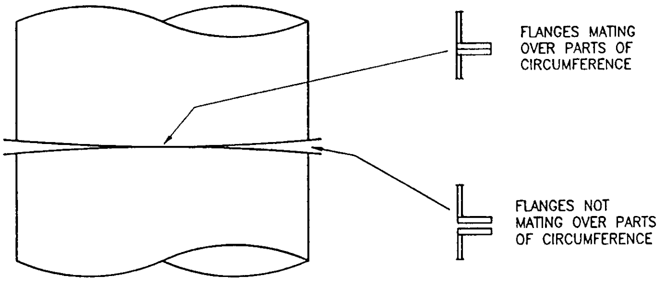

Fig. 2(b)

Effect of bolting flanges with lack-of-fit

Steel chimney shells are relatively flexible in tangential rotation and flanges with the angular type of distortion in Figure 2(a) can often be drawn together to mate with relatively small bolt tensions unless the flange is very stiff in torsion. However, this action distorts the shell and induces vertical bending stresses which have their maximum value where the shell plate meets the flange and where there is commonly a weld. In the case of gaps in the Figure 2(b) type of mismatch, a relatively small bolt tension can often draw the toes together but the shell is relatively stiff to axial loads and in many cases the bolt tightening force will not be able to draw the heels together. The operative can only see the toes and may well believe that because they are mating, and that the bolt is appropriately torqued, then the joint is satisfactory, but this is not so if there is a gap at the heel.

Whatever bolt force is required to draw the flanges to mate diminishes the balance available to precompress the mating surfaces.

Effect of wind loading on flanges with lack-of-fit

Figure 3 shows what can happen in non-mating parts of the flange circumference at the various stages of loading. Figure 3(b) illustrates the position after bolt tightening but with no wind load. In Figure 3(c) the load path for wind tension is shown. Because the flanges taper, the bolt seats eccentrically and the tensile force causes bending in the bolts. There is already a force magnification due to bolt eccentricity and the relative areas of bolt and shell; the wind stress in the bolt can be an order higher than that in the shell (by a factor of 30 typically). Thus, in fatigue terms a relatively modest stress range in the shell becomes highly significant in the bolts. When in compression, if the shell stress is sufficient to overcome the preload induced from the bolt tightening then the joint closes. With repeated tension and compression both the bolts and the shell in the vicinity of the flange become liable to high stress/low cycle fatigue and quickly fail, and/or the bolts become loose.

If the lack of fit is large and the shell/flange combination is stiff it may not be possible even to draw the toes together into contact as was the case in 3(b). Vertical wind stresses in the shell are then transferred through the bolt alone with associated angular movements of the flange and flexing of the shell. The flange movements cause bending of the bolts and both the bolts and the shell can again be liable to high stress/low cycle fatigue failure and/or the bolts loosen.

This phenomenon can, equally have other causations such as loose bolts or the use of soft gaskets or thick mastics in the joints.

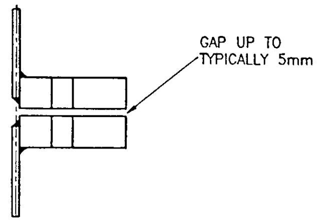

Fig. 3

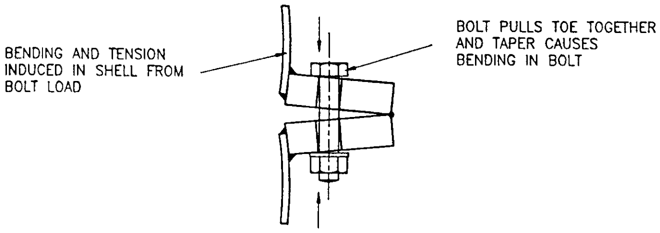

Fig. 3(b)

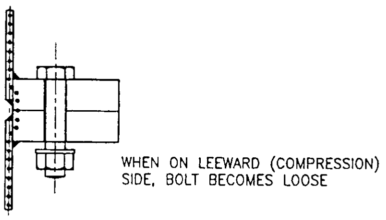

Fig. 3(c)

Quantification

The relationship between the bolt forces, flange rotation and shell stresses are governed by the stiffness chateristics of the shell. For long cylinders subjected to axisymmetric loadings at one end, the radial deflections and rotations are given by Roark. For non-axisymmetric loadings Rabich has developed a method based on using a Fourier series to define the deflections and derives the associated actions around the perimeter from which a stiffness matrix for each mode of the series can be developed. In this regard mode 1 is the axisymmetric case, mode 2 plain ovalling, mode 3 a three lobe form. For mode 1 longitudinal stiffness has no meaning, and this is applicable only to modes 2 and higher.

Conclusions

In order to prevent premature failure of flanged joints subjected to fluctuating tension forces it is essential that the flange faces mate properly and that bolts are installed correctly. The resistance of the joint to fatigue depends on precompression of the mating faces induced by bolt installation of sufficient magnitude that it does not become relieved under load.

Pairs of flanges should be match manufactured to ensure proper fit and the bolt installations should be properly specified and implemented.

Bibliography

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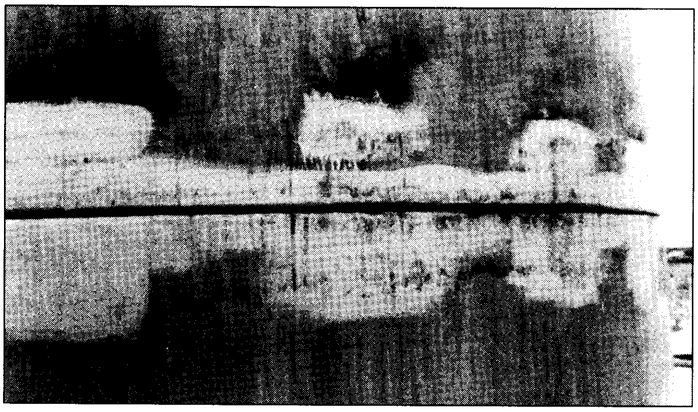
APPENDIX A — CASE HISTORIES

Case A1

Figure A1 shows the flanged joint at the 12m level of a 50m high chimney. Damage was noticed 23 months after construction when bolts failed on opposite sides of the chimney. The bolts were reported to have failed in fatigue and there was cracking (up to 70mm long) in the 8mm steel shell above the joint around the tops of the gussets. There was no cracking discovered in the comparable positions in the 10mm shell below the joint. After bolts had been replaced the toes were in contact but a survey of the heels showed gaps at positions coincident with the bolt failures and the shell cracks. See photograph.

Any opening/closing of the joint would have caused the flanges to rotate about the toes. The gussets would have the effect of increasing the stresses in the shell and concentrating them in the vicinity of the tips of the gussets. It was concluded that the mismatch of the flanges had allowed the bolts to become subject to high fluctuating wind stresses, and the shell to flex in the parts of the perimeter having the gaps between the flanges.

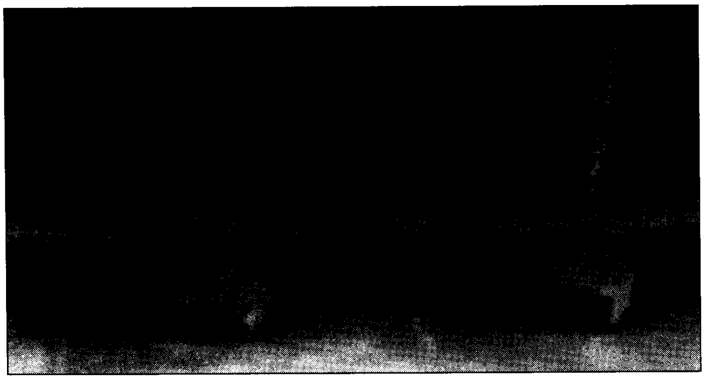


Case A1

Case A2

Figure A2 shows the flanged joint at the 80m level of a 100m high guyed chimney. Damage was noticed during a scheduled internal inspection some 9 months after the chimney had been commissioned. The main crack extended around one third of the perimeter and had a maximum width of 2 – 3mm. See photograph. No other distress or signs of plasticity were noticed so the gap can only have come from a gap of this width between the heels of the flanges. Failure of both the shell and the bolts was reported as being of the bending low cycle/high stress fatigue type.

A thorough dynamic analysis of the structure and subsequent deflection monitoring showed that a properly manufactured and installed joint should have had a very adequate factor of safety. However, an analysis based on an initial 2 – 3mm gap at the heel shows sufficiently high fluctuating stresses in both the plate and bolts to produce a mode of premature failure consistent with what was observed.



Case A2

Case A3

Figure A3 shows a flanged joint at the 28m level of a 80m tall chimney. Five years after erection and after severe winds (200 year return period wind speed) over one quarter of the bolts of the one joint were found to have failed. The bolts that had actually fractured are reported to have failed by low cycle/high stress fatigue. Some of the bolts tested were found to have shanks too long to permit the tightening torque to tension the bolts against the flanges, leaving the bolts loose.

There was no survey information to establish whether there was any degree of mismatch of the flanges.

It was concluded that the excessive winds allowed the flanges to part resulting in high fluctuating bolt loads, exacerbated by possible lack of pretension in the bolts (and therefore of precompression between the flanges).

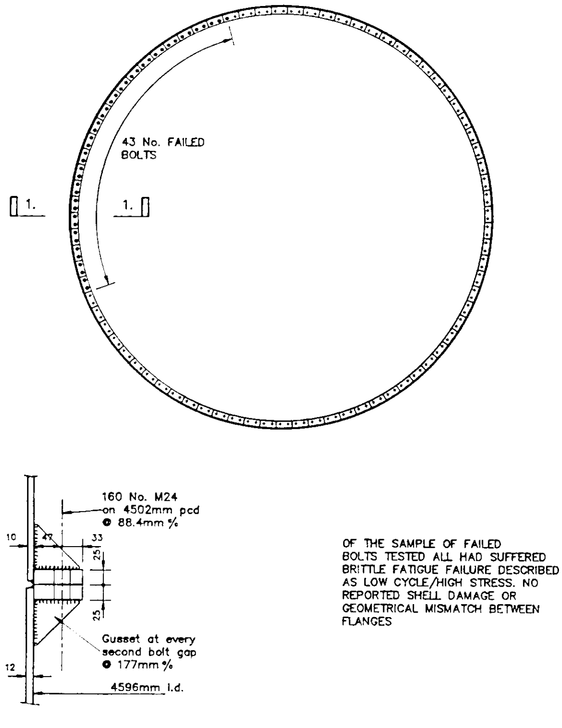


Fig. A3

Case A4

Figure A4 shows the flanged joint at the 19.8m level of a 30m tall tower, one of over one hundred similar structures at one site. Damage was noticed shortly after erection when cracks appeared at the flange to shell joint as indicated. One bolt is reported to have failed in fatigue and others were bent. Inspection of other completed joints showed some of them to have gaps between the faces over parts of the circumference of up to 5mm. Similar degrees of mismatching were found in the flanges of sections of structures yet to be erected.

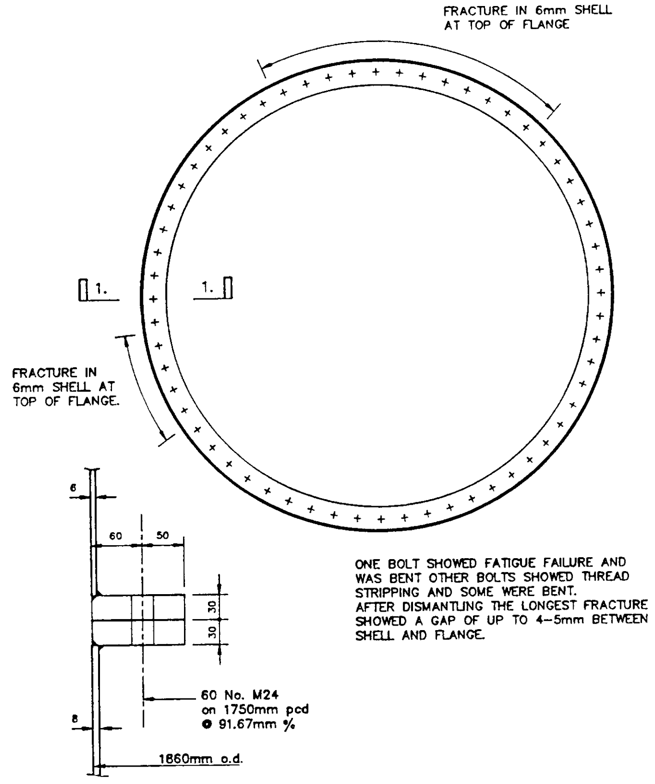


Fig. A4

It was discovered that the bolt installation had been specified as to be by the part-turn method. This is only suitable where the flanges are initially in contact. Where they are not, the bolts will only draw the faces closer together by a distance corresponding to one third to one half of the pitch of the bolt (in this case by about 1mm), leaving a gap between the flanges and bolts with very little tension in them. It was concluded that failure was due to high fluctuating stresses in shell and bolts due to the gaps between the flanges.

On repair and re-erection the bolts were installed by torquing and the gaps were able to be closed. Other non-failed joints were treated similarly. The degree to which there is residual precompression between the mating surfaces in some areas remains uncertain.