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Partially open crack model for leakage pressure analysis of bolted metal-to-metal flange

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ABSTRACT

Predicting the leakage condition is of primary importance when designing metal-to-metal flanges. The gap between flange surfaces is regarded as a partially open crack with a zero stress intensity factor, then a model based on fracture mechanics is proposed for predicting leakage pressure. An analytical solution was found, with weight function, considering the condition of crack front at the most internal point of the bolt hole. Finite element and experimental tests validated the effectiveness of the model. In addition, the dependencies on the main flange dimensions were investigated and discussed, providing useful guidelines for optimal flange design.

1. Introduction

Large centrifugal compressor cases are usually manufactured in two halves, connected by a bolted (or studded) flange. Although using a gasket is strictly recommended for pressure vessels [1], this leakage prevention technique cannot be used for the kind of flange investigated here, primarily because the bolted perimeter is open at the two ends in order to allow the shaft to pass through. This flange is usually called *gasketless*, or *metal-to-metal*, and the leakage of the pressurized fluid inside the vessel is prevented by the bolt preload. Bolted flanges have been widely investigated, however most studies are limited to the compact geometry design for connecting pipes [2–13], while others are dedicated to the deformation behavior of the gasket [14–20]. Research on flanges is usually focused on the structural stiffness, stress distributions, and the strength optimization of the flange parts, under bolt preload and internal pressure or other external loadings [2,3,6–12,18,21–29]. The main information from the literature, on metal-to-metal flange leakage, regards the following:

1. The leakage rate is notably affected by the flange surface microgeometry [4,5,17,30–32]:
   - accurate *surface flatness* is required to avoid local contact discontinuity or limitation of the contact pressure;
   - reduced *surface roughness* is recommended in order to prevent micro-leakage;
   - *roughness orientation* not parallel to the main leakage flux direction reduces the leakage rate.
2. The leakage promoted by unavoidable surface unevenness, and/or poor surface roughness, can be reduced by specific sealants (e.g. any silicone based sealant) in order to fill in local irregularities on the surfaces, which would otherwise be difficult to compensate for by metal deformation produced by the bolt tightening [4,33].

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Nomenclature

LEFM	Linear Elastic Fracture Mechanics
SIF	Stress Intensity Factor
WF	Weight Function
FE	Finite Element method or Finite Element analysis
K	mode I SIF
a	crack length
x	local coordinate
$h(x,a)$	weight function
a_o	partially open crack length
$\sigma_n(x)$	nominal stress distribution
$\sigma_0,\ \sigma_1$	nominal stress parameters
$K_0,\ K_1$	weight function integrations for uniform and linear nominal stresses
$\beta_0,\ \beta_1$	uniform and linear SIF coefficients
D_V	vessel diameter
t_V	vessel wall thickness
P_B	bolt pitch
H	flange half height
H_S	stud height
W	flange width
Z	bolt axis position
d_H	bolt hole diameter
d_B	bolt stem diameter
d_N	nut circle diameter
d_t	stud thread diameter
d'_H	model equivalent bolt hole diameter
L	flange leakage length
L_o	flange opening length
σ_B	bolt preload stress
p	vessel internal pressure
F_B	bolt preload force
F_p	internal pressure opening force
α	compressive stress distribution angle across the flange height
$F_1,\ F_2$	bolt pressure distribution compensation forces
$\sigma_{n,B}(x)$	nominal stress distribution, bolt preload component
$\sigma_{n,p}(x)$	nominal stress distribution, internal pressure component
$\sigma_{n,B1}(x)$	nominal stress distribution with unitary bolt preload stress
$\sigma_{n,p1}(x)$	nominal stress distribution with unitary internal pressure
$K_{L,B1}$	SIF with unitary bolt preload stress
$K_{L,p1}$	SIF with unitary internal pressure
C_β	weight function combination coefficient
p_L	leakage pressure: the value of the internal pressure that causes leakage
p'_L	leakage pressure, with no pressure at the partially open flange surfaces
$p'_{L,max}$	maximum leakage pressure, among the investigated vessels
$p'_{L,FE}$	leakage pressure predicted with the FE model
$\Delta p'$	relative difference between analytical and FE models

3. The onset of leakage is usually associated with the loss of contact (zero pressure) between the flange mating surfaces [7,8,23,21,33], or after a critical tensile stress (usually a few MPa) required to break the sealant film [33,34].
4. Bolt preload scatter, which generates leakage unreliability, is caused by many factors such as uncertainty of the torque wrench relationship to preload force, bolt tightening sequence and subsequent relaxation, and even thermal effects [24,35–38].

In conclusion, although the literature is useful in terms of surface preparation, there has been no a physical description of the metal-to-metal flange leakage. We present a model which finds the value of the internal pressure that generates the leakage. This model is based on the equivalence between the flange surfaces and a partially open crack. The flange surfaces are assumed as being plain and initially flat, only deformed by the opening effect of the internal pressure, which is compensated for by tightening the preloaded bolts (or studs). The leakage was modeled as the condition when the opening front reaches the most internal point of the bolt hole, from where the fluid can exit. The use of the weight function technique, after some