Dynaflow Research Group

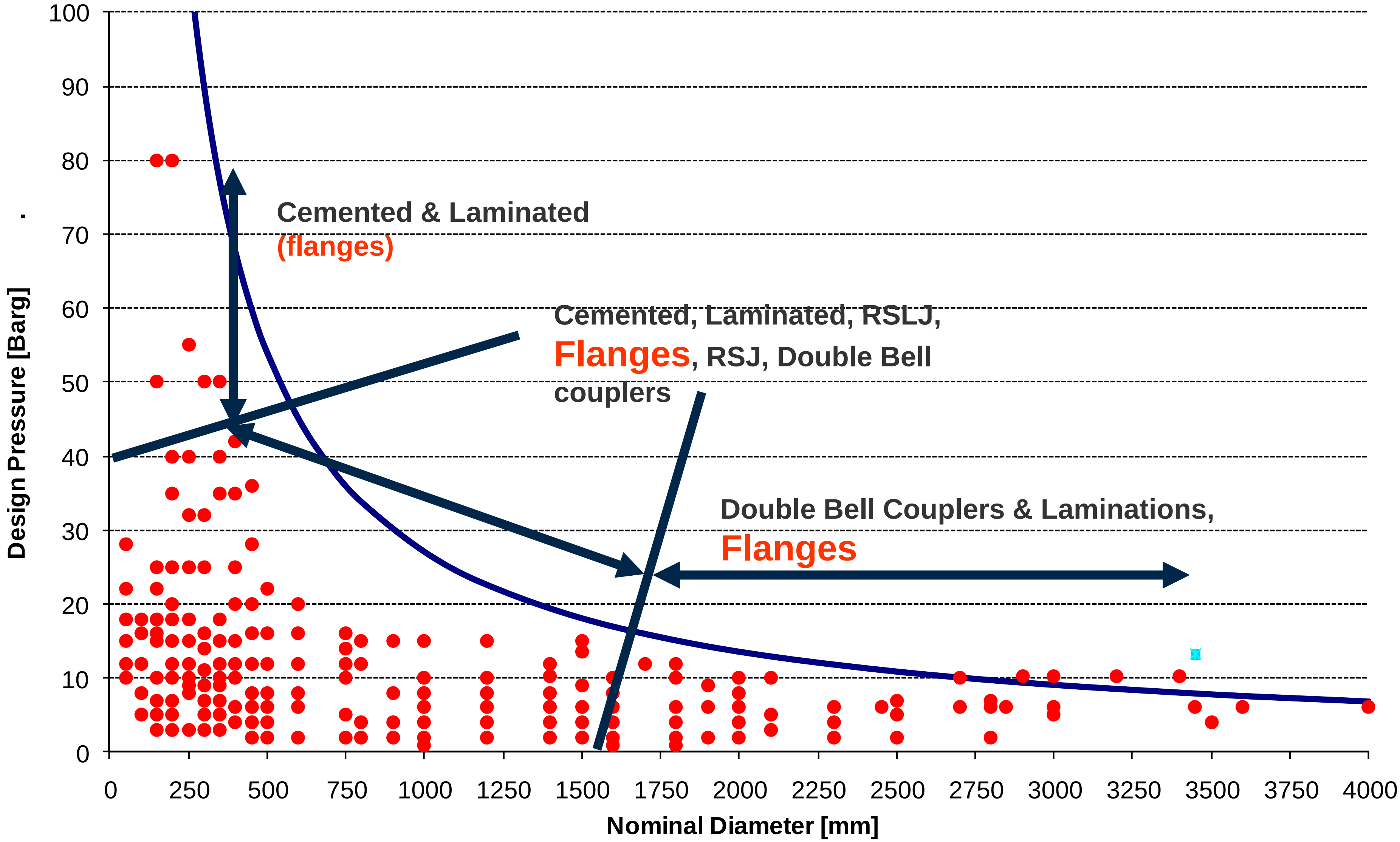
GRP Flanges design & assessment

Rotterdam, 10 March 2011

Scope

1. Introduction
2. Flange failures & flange design
3. Flange qualification & load assessment methods
4. Present ISO 14692 approach and update

FRP pipe pressure versus diameter Jointing systems



Glass Reinforced Flanges NB 4000 mm

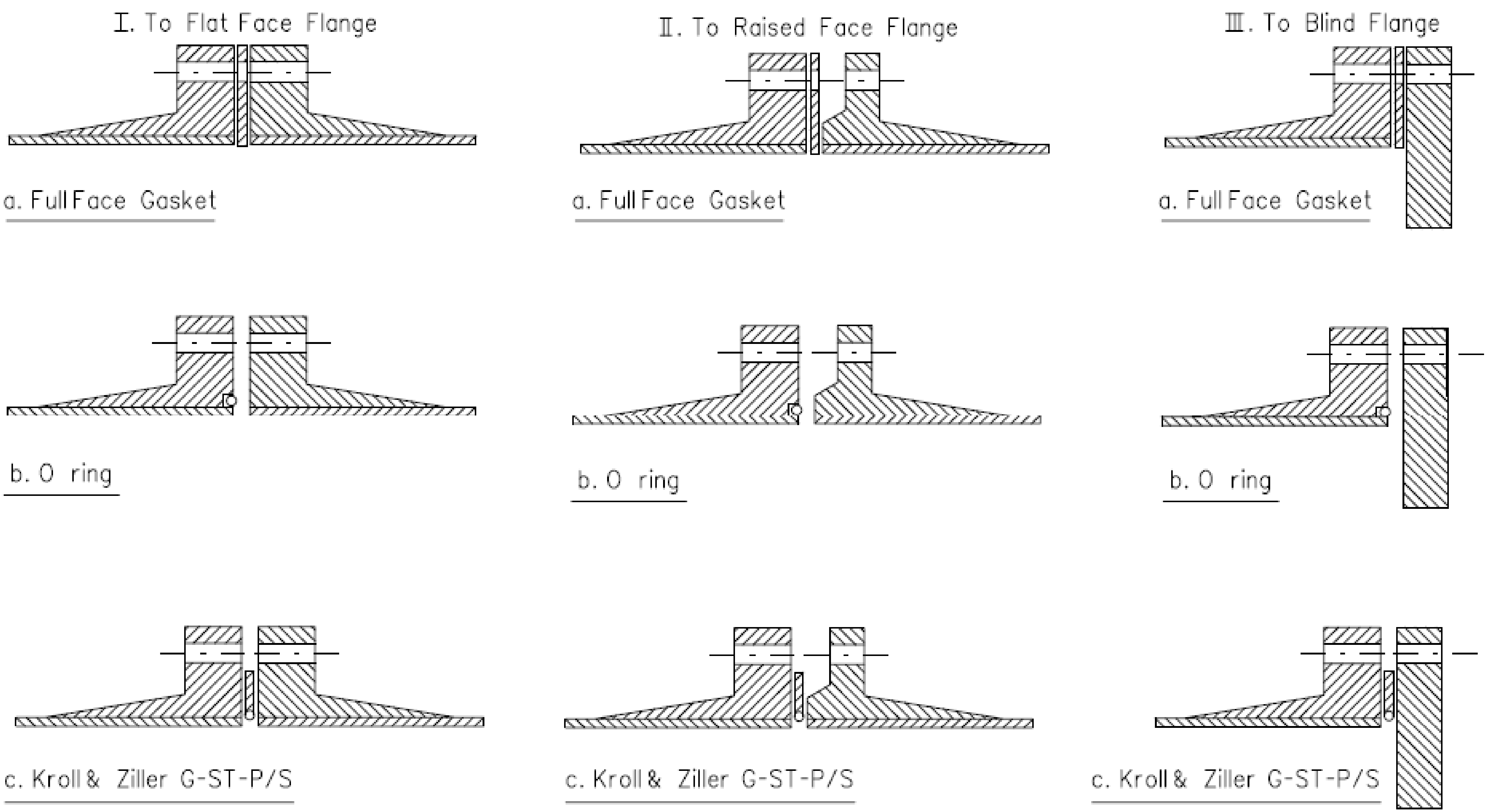
Shortcomings of present GRP codes

- Flange assessment (for combined loading)
- SIF's and flexibilities
- Local Buckling of large bore U/G headers (limited effect of side support)
- Interference of underground pipes
- A/G supporting of large bore headers

Various types of flanges and manufacturing methods

- Hand lay-up
- Transfer (compression) Molded
- Circumferentially Wound
- Flange resins:
  - Epoxy
  - Vinylester
  - (Polyester)
- Rigid flanges
  - Integral Flanges
  - Cemented flanges
- Loose flanges

Flange Connections



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Flange Failure Modes Definition

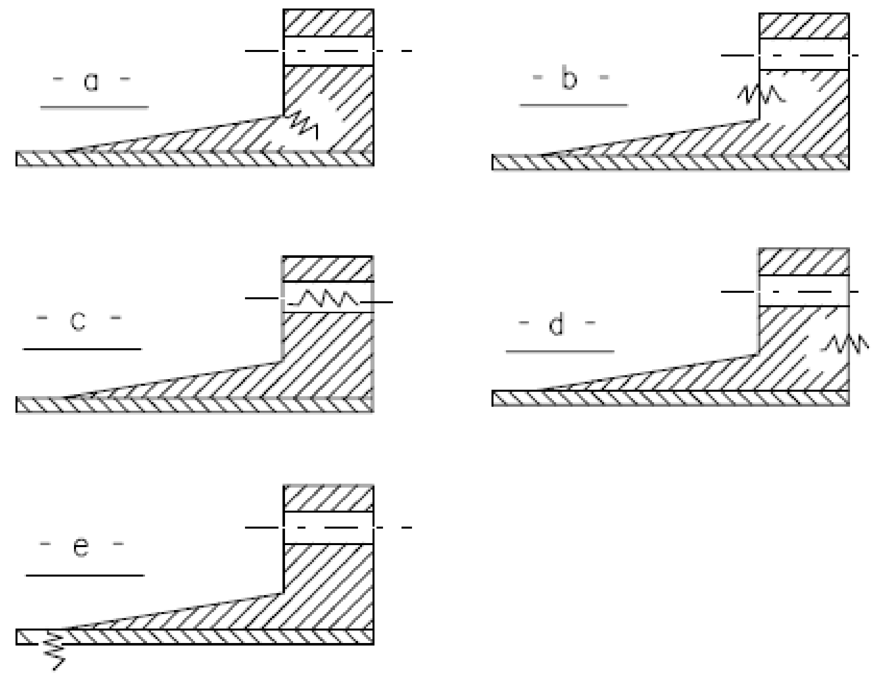
a. Crack at hub neck.

b. Crack within washers edges at Flange back.

c. Crack in the hole area, not visible at flange face or back.

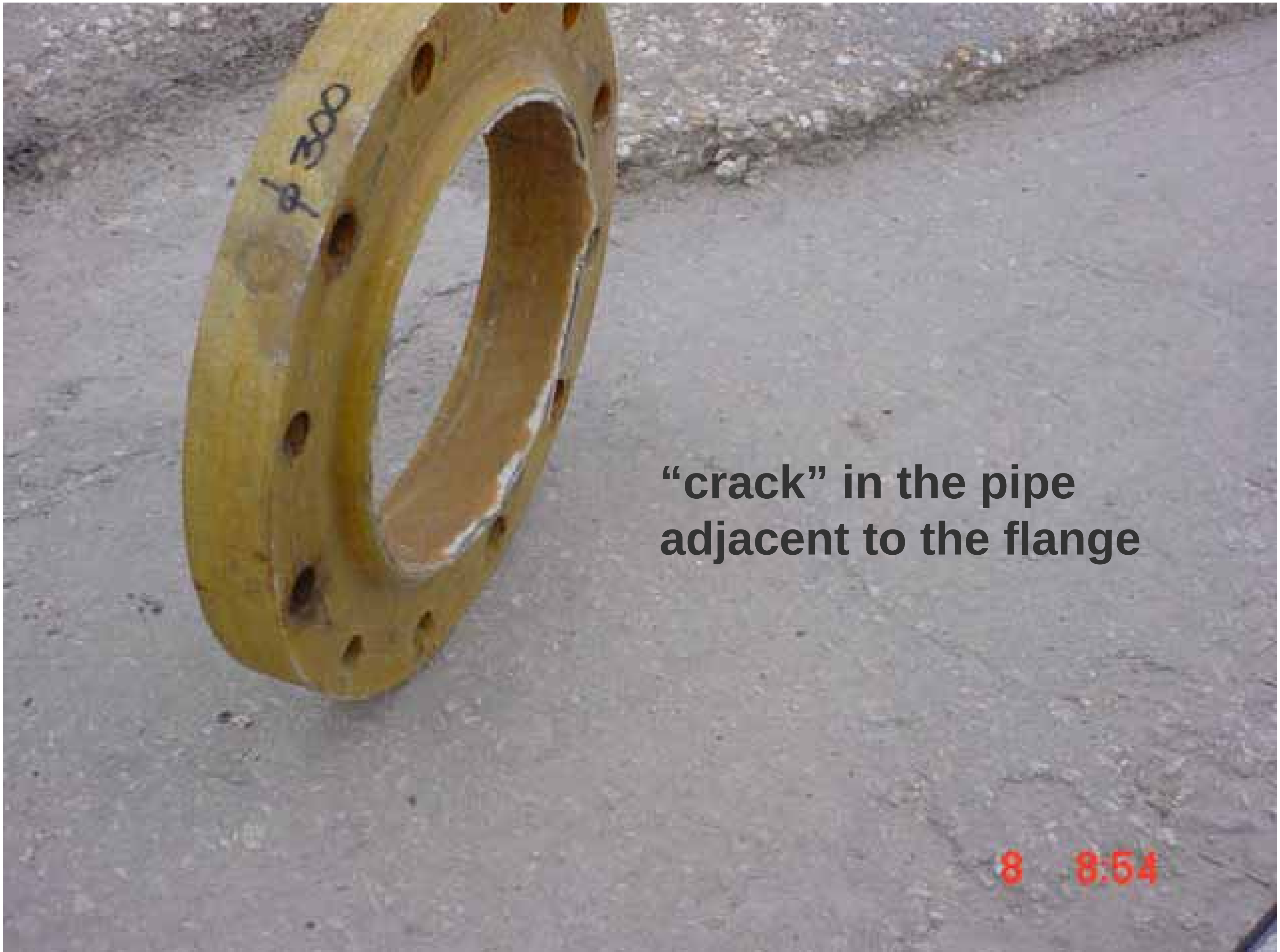
d. Crack anywhere on the Flange face.

e. Crack in the Pipe



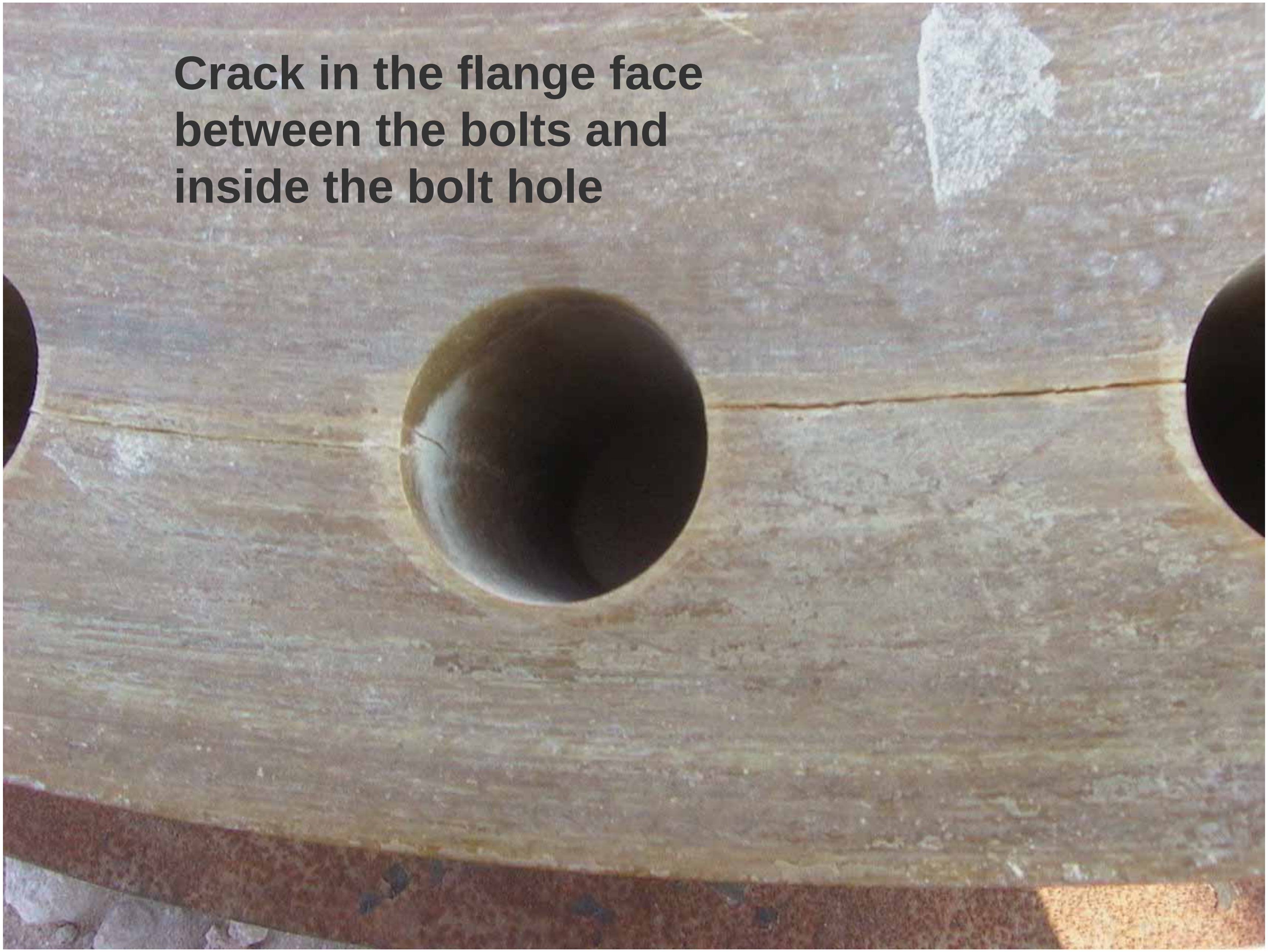
EXAMPLE

“Crack” in the pipe adjacent to the flange



“crack” in the pipe adjacent to the flange

Crack in the flange face between the bolts and inside the bolt hole



Crack at the hub neck

Crack at the hub neck

Sheared flange starting with crack at the neck of the hub

Crack at the hub neck

EXAMPLE


Crack at the hub neck

EXAMPLE

“crack” at the “hub neck”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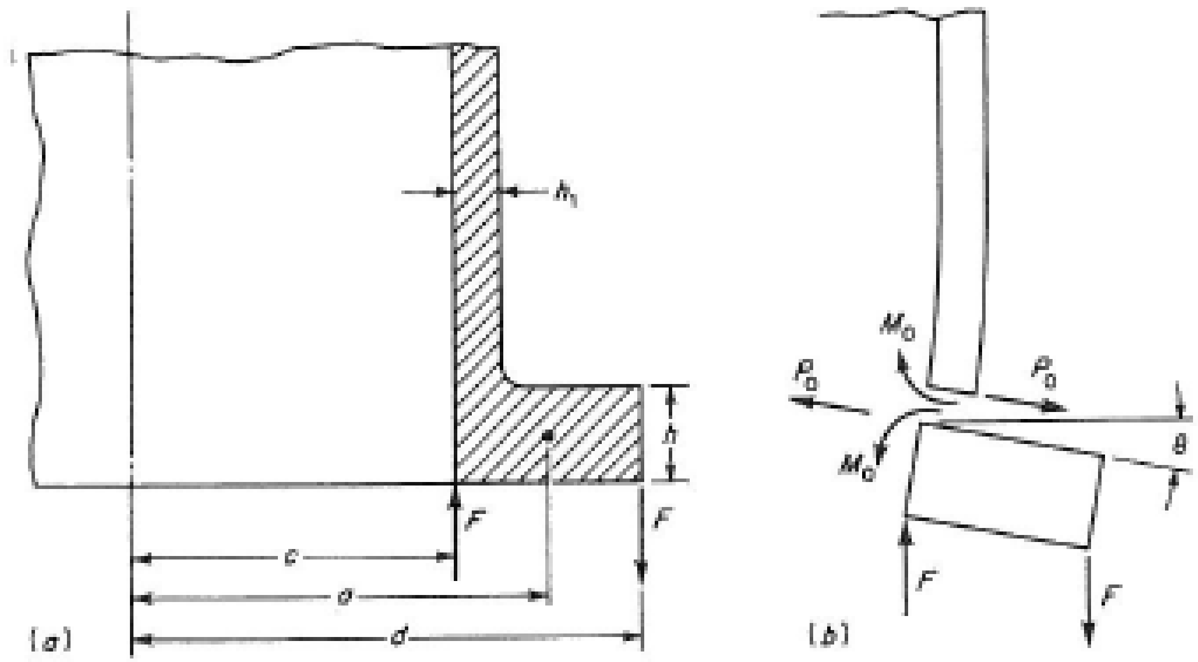
Intermediate conclusion

- Cracks at the hub neck are the dominating failure mechanism
- Cracks at the hub neck are often catastrofic

Cracks at the hub neck are related to a match-up problem between flange ring and connected pipe



$$\theta = \frac{M_t}{k_{pipe} + k_{flangering}}$$

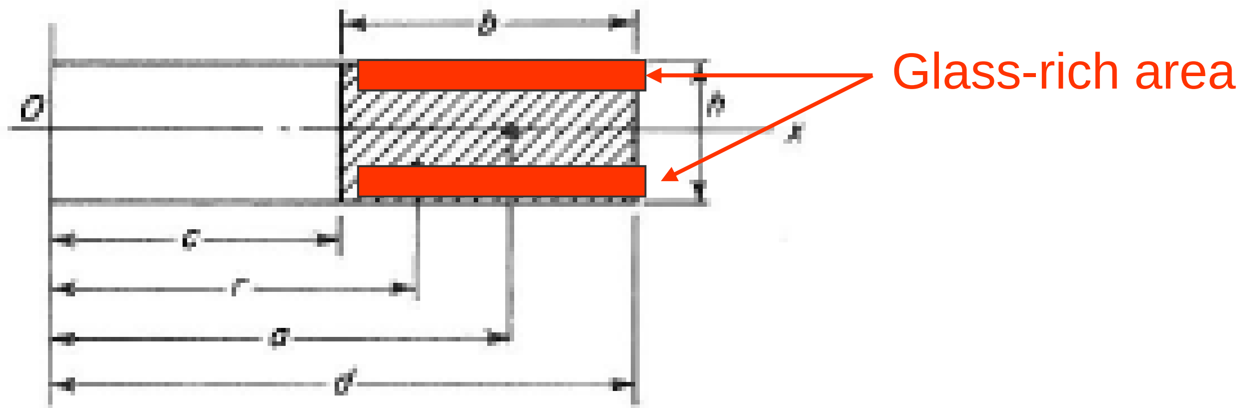
$$k_{pipe} \approx f_1(\sqrt{D * t_{pipe}}) * E_{axial,pipe} * t_{pipe}^3$$

$$k_{flangering} \approx f_2(D_o, D_i) * E_{circumferential,flangering} * t_{flange}^3$$

Flange design:

Delicate balance between:

1. Stiff flange ring (minimizing flange ring rotation)
2. Sufficient strength in transition between flange ring and connected pipe to bridge the deflection difference



Flange ring deflection (rotation) governed by moment of inertia around x-axis

$$I_x \sim h^3 * E_{circ}$$

Potentially circumferential glass in a thick flange results in the highest Ix values

Flange Cracking is hindering FRP application and has to be eleminated

Gross flange failure is initiated by cracks and is catastrophic

Flange cracks are relatively common (more common in larger bore flanges)

- A cracked flange is “normal”
- Most cracks are superficial (only in resin rich area and not penetrating into reinforced flange body)

Origin of Flange cracks

- Torque of the bolts
- Excessive external loads (moments)
- Application of wrong gasket
- Defective flange design
- Defective flange production

Superficial cracks ??

Superficial cracks ??

Scope

1. Introduction
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Flange Assessment/Design methods:

Some only internal pressure

External loads incorporated as increased internal pressure (equivalent pressure)

Common Assessment Items:

1. Longitudinal Stress in Hub
2. Radial Stress in the flange
3. Tangential/Circumferential Stress in the flange
4. Largest combined stress (Hub + Flange)
5. Radial stress at the bolt circle

Dedicated FRP codes

- **ASME B&PV Section X**
- **ASME RTRP**

Metal (Isotropic) codes:

- **AD Merkblatter**
- **RToD D-0701**
- **EN 13480**
- **EN 1591**
- **UNI 2231**

Key:

What is allowable stress??

Depends on location and flange manufacturing method

Based on supplier experience??

Based on tests??

Crack at the hub neck due to external moments??

EXAMPLE

Flange Failure due to external loads??

Flange verification:

Conform ASME RTP-1

1. Internal pressure only
2. Allowable stress 4600 psi (supplier experience??)

- DN700(28") - Design of Flat-Face Integral Body Flanges With Full-Face Gaskets

Design Conditions			Gasket and Bolting Calculation	
Design pressure	87	psi	Gasket details	G= C − 2h_G= 31.34 in
Design temperature	180	°F		b= (C−B)/4= 0.8 in
Atm. temperature	41~122	°F	Flange details	y= 40 psi
Flange material	GRP			m= 0.5
Bolting material				
A= 32.94 in	B= 28 in	C= 31.31 in	$h_G = \frac{(C-B)(2B+C)}{6(B+C)}$ = 0.8 in	$h'_G = \frac{(A-C)(2A+C)}{6(C+A)}$ = 0.4 in

Allowable bolt stress	Oper. Temp.	S_b	14500 psi	H_p = 2bπGmP = 6849.2 lb	H_G= bπGy = 3149 lb
	Atm. Temp.	S_a	14500 psi	$H = \frac{G^2 \pi p}{4}$ = 67079 lb	
Allowable fl'g stress	Oper. Temp.	S_{fo}	4600 psi	$H'_p = \left(\frac{H_p}{H'_G}\right) H_p$ = 13098.4 lb	$H'_G = \left(\frac{h_G}{h'_G}\right) H_G$ = 6298 lb
	Atm. Temp.	S_{fa}	4600 psi	W_{m1}= H_p +H+ H'_p = 87626.6 lb	W_{m2} = H_G + H'_G = 9447 lb
Bolting Requiremen A_m = greater of $\frac{W_m}{S_b}$ and $\frac{W_{m2}}{S_a}$ = 6.0 psi			A_b = 14.5 psi	W_a= 0.5(A_m + A_b) S_a = 148625 lb	

Flange Moment at Operating Condition

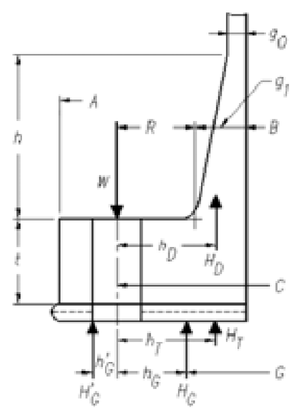
Flange Loads (operating condition)	Lever Arms	Flange Moments(Design Cond.)
H_D= πB²p/4 = 53543 lb	h_D = R + 0.5g_1 = 1.1 in.	M_D = $H_D h_D$ = 58897 in-lb
H_T= H − H_D = 13536 lb	h_T = 0.5(R+g_1+h_G)= 1.3 in.	M_T = $H_T h_T$ = 17597 in-lb
		M_o = M_D+M_T = 76494 in-lb

Flange Moment at Gasket seating Condition

Flange Loading (Bolting-up Condition)	Lever Arms	Flange Moment (Bolting-up Condition)
H_G = W_a−H= 81546 lb	h''_G = ($h_G h'_G$)/(h_G + h'_G) = 0.3 in.	M_G= $H_G h''_G$ = 24464 in-lb

M_{max} grater of M_o or $M_a x \frac{S_{fo}}{S_{fa}}$	(Equivalent checking for Mo at allowble flange stress of S_{fo} and separately for M_a at allowble flange stress of S_{fa})	$M = \frac{M_{max}}{B}$ = 2731.9 psi

Stress Calculation				Shape contants			
Longitudinal hub stress	S_H = fM / λg_1^2	=	2710.2 psi	K= A / B =	1.2	h_o = (Bg_o)^1/2 =	2.9
Radial flange stress	S_R = βM / λt²	=	1896.8 psi	T=	1.9	h/h_o =	1.1
Tangential flange stress	S_T = (MY / t²) − ZS_R	=	-361.3 psi	Z=	5.8	F =	0.65
Greater of	0.5(S_H+S_R) or 0.5(S_H+S_T)	=	2256.5 psi	Y=	12	V =	0.02
				U=	14	f =	1
Radial stress at bolt circle = $S_{RAD} = \frac{6M_G}{t^2(\pi C - Nd_1)}$		=	717.8	g_1/g_0 =	4.0	e = F / ho =	0.2



$d = \frac{U}{V} h_o g_o^2$	=	183	
t	=	1.8 in	45 mm
α = te + 1	=	1.36	
β = 4/3 te + 1	=	1.5	
γ = α / T	=	0.7	
δ = t³ / d	=	0	
λ = γ + δ	=	0.7	
Pipe thickness (g_o)	=	0.3 in	7.5 mm
g_1 = g_o + t / 2	=	1.2 in	
R = C−B/2−g_1	=	0.5 in	
N = No.of bolts	=	40 EA	
d_1 = Dia.of Bolt holes	=	0.88 in	

2. References

2.1 Standard Practice for Fiber Reinfoced Plastic Pressure vessel. 1998 ASME Section X.

2.2 Standard Practice for Reinfoced Themoset Plastic Crrosion Resisyant Equipment. 1995 ASME RTP-1

2.3 Standard for pipe flange and flanged fitting. 1994 ASME/ANSI B16.47 SERIES "B"

3. Conclusion

3.1 Checking table for allowble stress

Checking Item	Stress for Calculation		Allowble Stress	Result
Longitudinal stress in hub	2710 psi	<	4600 psi	OK
Radial stress in flange	1807 psi	<	4600 psi	OK
Tangential stress in flange	-361 psi	<	4600 psi	OK
Greater of combined stress	2259 psi	<	4600 psi	OK
Radial stress at bolt circle	718 psi	<	4600 psi	OK

3.2. Flange thickness is no problem by manufacture calculation.

3.3. It can be concluded that the resultant flange thickness of GRP is ;

- Recommend Manufacture's Flange Thickness is; **t = 1.8** in

45 mm


7 8 9 10 11 12 13 14 15 16 17 18 19
FRANCE

External flange loads are important

How to address external loads

1. **Present practice incl present issue of ISO 14692**
2. **Iso 14692 revision (2011-2012)**

GRP Flange qualification conform current issue of ISO 14692

6.2.3.3.4 Flanges

Flanges shall be qualified according to either of the following:

— procedures given in 6.2.3.3.1, 6.2.3.3.2 and 6.2.3.3.3 using higher rated gaskets and seals as applicable, provided they are of the same type as specified during service;

— ASTM D4024 for reinforced-thermosetting-resin flanges other than contact-moulded flanges or ASTM D5421 for contact-moulded flanges.

The method of qualification shall be agreed with the principal.

Flanges qualified by

A. 1000 hr Qualification tests conform ASTM D1598

B. Testing conform ASTM D4024 / D5421

Flange Qualification

ASTM D5421 & D4024

- **Pressure performance based**
- **Short term rupture = 4 x rated pressure**
- **External Loads???**
  - **Equivalent pressure rule??**

6. Performance Requirements

6.1 The following performance requirements are intended to provide classification and performance criteria for the purpose of qualification testing and rating of prototype constructions and periodic reevaluation of the manufacturer's stated ratings. They are not intended as routine quality assurance requirements for production runs of rated flanges.

6.2 Flanges shall meet the following performance requirements when joined for testing according to the manufacturer's recommended practice for field installation:

6.2.1 *Sealing*—Flanges shall withstand a pressure of at least 1.5 times the rated design pressure without leakage when tested in accordance with 10.4.

6.2.2 *Short-Term Rupture Strength*—Flanges shall withstand a hydrostatic load of at least four times their rated design pressure without damage to the flange when tested in accordance with 10.5.

6.2.3 *Bolt Torque*—Flanges shall withstand, without visible sign of damage, a bolt torque of at least 1.5 times that recommended by the manufacturer for sealing of the flange at its rated pressure when tested in accordance with 10.6.

External loads incorporated by means of Equivalent pressure rule (ASME B&PV Section III NC 3658.1 but also e.g. RToD D0701)

(b) The Design Pressure used for the calculation of H in Appendix XI shall be replaced by a flange design pressure

$$P' = P + P_{eq}$$

The equivalent pressure P_{eq} shall be determined by the greater of:

$$P_{eq} = 16M_{fs} / \pi G^3$$

or

$$P_{eq} = 8M_{fd} / \pi G^3$$

$$P_{internal} + P_{equivalent} < P_{rating}$$

Equivalent pressure rule

$$P_{internal} + P_{equivalent} < P_{rating}$$

$$P_{equivalent} = 16*M/(\pi*G^3)*(\text{Koves factor } F_k) + 4*F/(\pi*G^2)$$

Koves factor F_k:
External moment factor to account for difference in local stress and local rotation due to an equivalent axial force vs a bending moment

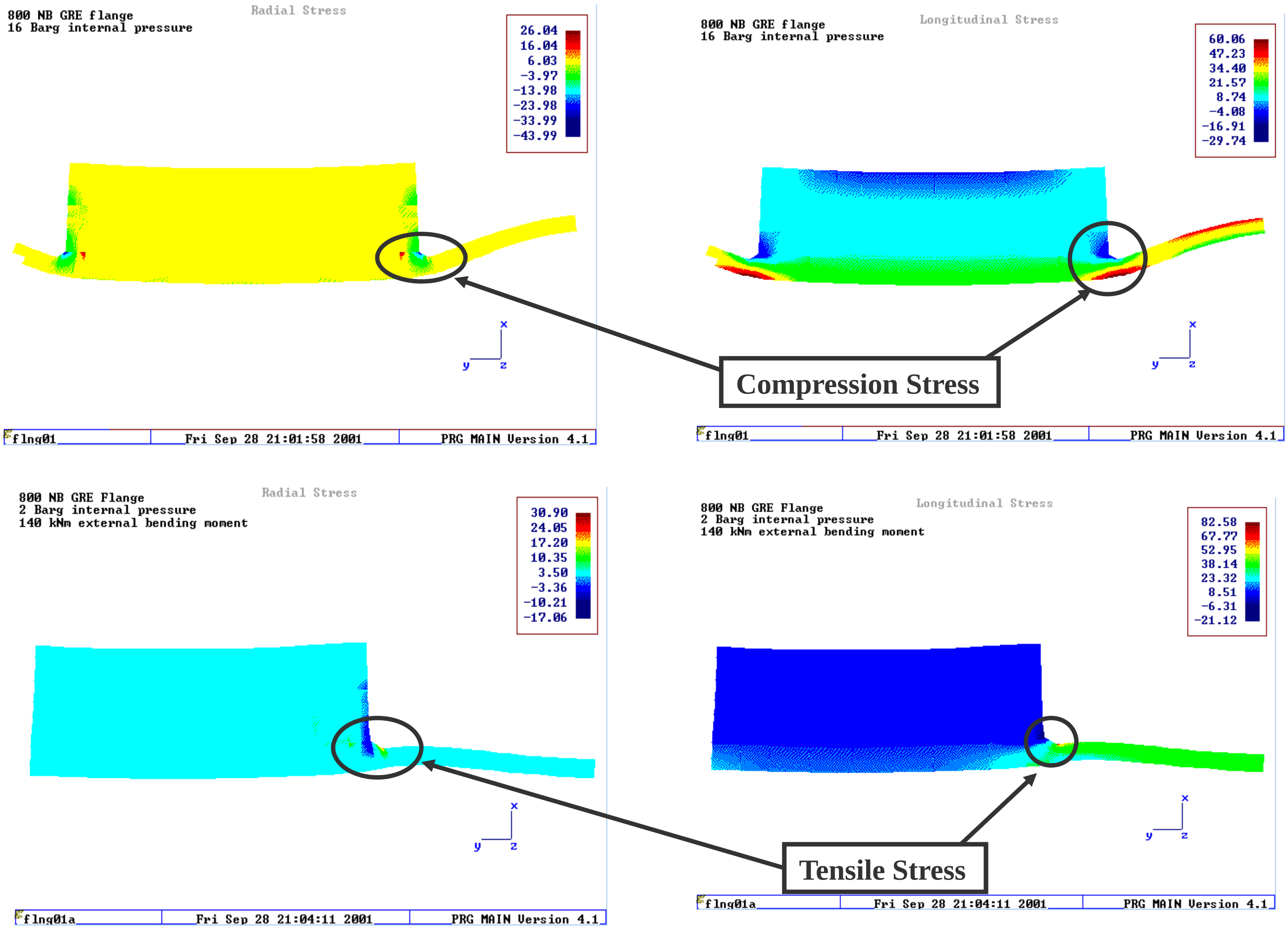
$$F_k = \frac{1}{1 + \frac{G*J}{E*I}} \leq 1$$

J = Polar Moment of Inertia of flange cross-section
I = Bending Moment of Inertia of flange cross-section

Two questions:

1. Is the equivalent pressure approach also a valid approach for GRP flanges?

2. Is the Koves factor (smoothing the effect of moment loads) valid for GRP flanges.??



FE-Check of equivalent pressure rule

EXAMPLE

Flange failure due to local loading

Flange failure due to local loading (fish plates)

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Flange Assessment/Design methods:

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- **ASME B&PV Section X**
- **ASME RTRP**

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Common Assessment Items:

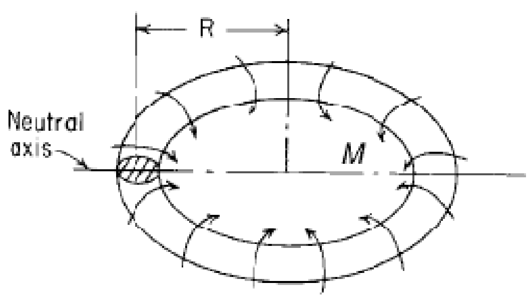
1. **Longitudinal Stress in Hub**
2. **Radial Stress in the flange**
3. **Tangential/Circumferential Stress in the flange**
4. **Largest combined stress (Hub + Flange)**
5. **Radial stress at the bolt circle**

Alternative method:

1. **Flanges fail due to strain:**

Simplified Design Method

- **Flange rotation criterion: 1 deg.**



$$\sigma = \frac{MR}{I/c}$$

$$\theta = \frac{MR^2}{EI} = \frac{\sigma R}{Ec}$$

Objective of new approach in ISO 14692 revision

For flange manufacturer

- Qualification criteria for family representative flanges
- Scaling rules for family member flanges

For Engineer

- Generation of allowable flange load envelope

GRP Flange qualification conform current issue of ISO 14692

6.2.3.3.4 Flanges

Flanges shall be qualified according to either of the following:

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The method of qualification shall be agreed with the principal.

Flanges qualified by
A. 1000 hr Qualification tests conform ASTM D1598
B. Testing conform ASTM D4024 / D5421

Note:
+ Draw back of qualification method: Internal pressure loading only
+ Simulating external loads by increased qualification pressure??
+ How to scale other flanges from test results

Five points

1. Pressure rating:

- **Flanges are rated using MPR: MPR = f2 * Pq (f2 = 0.67)**

2. Flange qualification:

Flanges are qualified to Pq by means of:

- **Short term cyclic loading and vacuum testing**
- **1000 hr survival testing**

3. Flange scaling

- **Flange scaling within product sectors based on stress as per ASME RTP-1=2005.**
- **In addition requirement on minimum flange rigidity as per ASME B&PV Sect VIII div 1 appendix 4**

4. Long term flange load envelope

- **The long term design envelope is demonstrated by combined load testing on representative flange joints**

5. System design conform Equivalent pressure method and flange design envelope.

Flange Qualification

Items to be demonstrated:

1. Long term strength over the design life of the flange
2. Leak tightness of the flange gasket combination at operating and hydrotest conditions
3. No flange damage at operating and hydrotest conditions
4. Verification of recommended maximum bolt torque in combination with gasket for flange damage.
5. Verification that gasket, flange bolt torque combination can withstand vacuum

1.Long term strength by means of 1000 hr survival test (Arrangement A) and 2.Leak tightness test (Arrangement B)

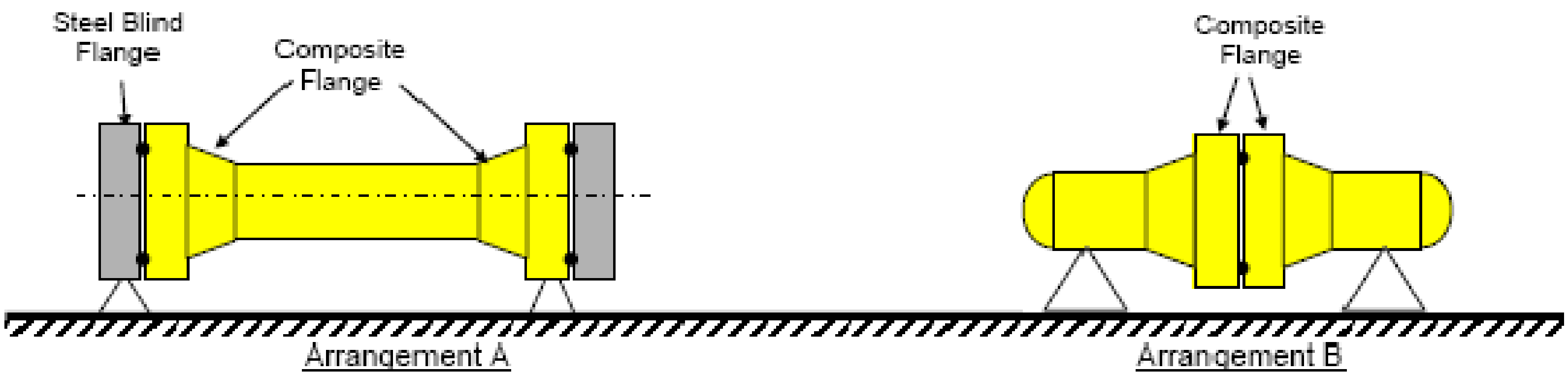

Figure 1; Sample arrangement for 1,000 hrs survival testing

1. In the survival test (at temperature) the flange is allowed to show damage but no failure (e.g. leakage) within the 1000 hr.

2.The leak test (at ambient) is done by 10 pressure cycles for 5 min at 1.5 * MPR
Followed by a vacuum test at -0.5 Barg.
Leakage is considered a test failure.

Applicable 1000 hr test pressure
Based on ISO defined fixed ratios typically 2.1-2.7 x MPR

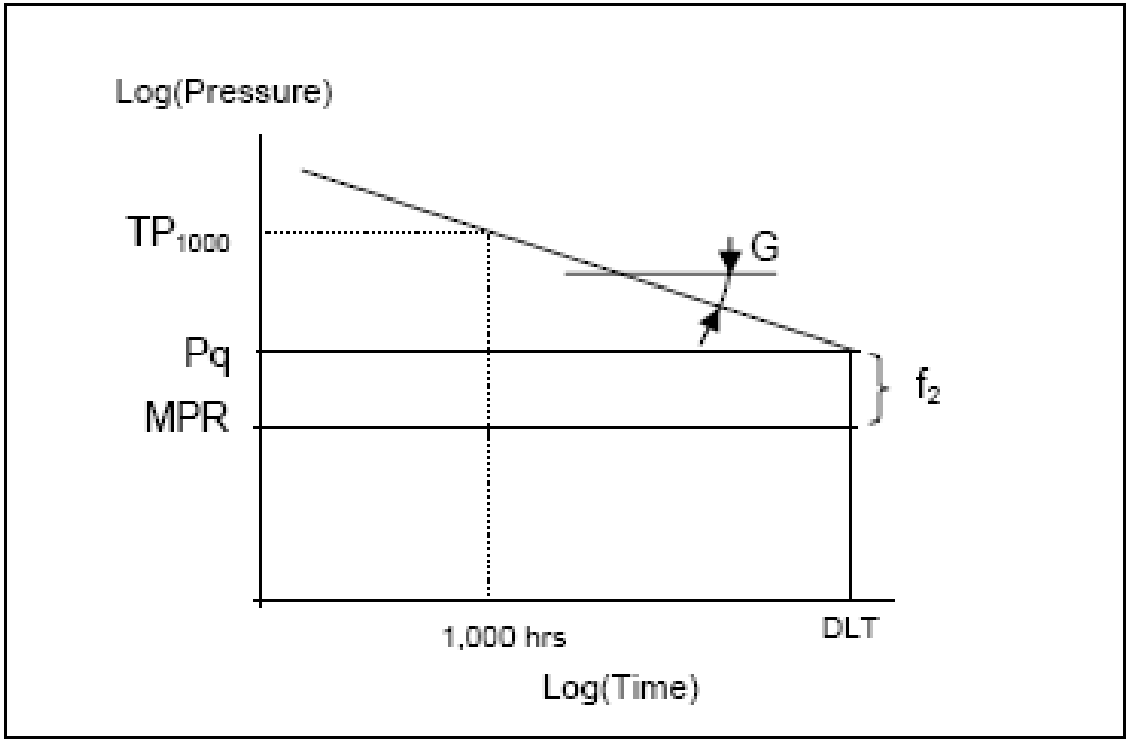

Figure 4; Determination of MPR by means of 1,000 hrs survival test

Figure 2; Sample DN1500 PN6 for survival test at elevated temp.

Figure 3; Sample DN2300 PN6 for survival test at ambient temp.

Flange scaling rules

Flange scaling rules are as per ASME RTP-1-2005

Based on dimensions of qualified (family representative) flange representative stress values are determined that can be used in scaling the dimensions of other flanges in the same product sector

The requirement in NM12-370 that the minimum hub thickness is 50% of the flange thickness is dropped because of interference with the bolt circle.

Similar consideration for hub length. Hub length to be based on minimum shear length.

Additional flange rigidity check is added (rigidity index between 1.0 and 1.5 at MPR

Flange Type[4]	Rigidity Index
Integral type flanges:	$J = \dfrac{52.14 \cdot V \cdot M_0}{L \cdot E \cdot g_0^2 \cdot K_I \cdot h_0}$
Loose type flanges with hubs	$J = \dfrac{52.14 \cdot V_L \cdot M_0}{L \cdot E \cdot g_0^2 \cdot K_L \cdot h_0}$
Loose type flanges without hubs and optional flanges	$J = \dfrac{109.4 \cdot M_0}{E \cdot t^3 \cdot K_L \cdot LN(K)}$

Table 1: Flange Rigidity Index J
(re-produced from ASME VIII Div.1 Appendix 2 [3])

Where:

E = Modulus of elasticity for the flange material at design temperature (operating condition) or at atmospheric temperature (gasket seating condition).
K_I = rigidity factor for integral flanges = 0.3.
K_L = rigidity factor for loose type flanges = 0.2.
J = rigidity index.

Long term flange envelope

1. Long term flange envelope is demonstrated by supplier by means of 1000 hr combined load tests on a 600 NB and a 1200 NB flanged joint

2. Test to be done at temperature. Therefore if required higher rated gaskets (but of same type) may be used.

3. Two tests: 1. At the 1000 hr qualification pressure & 2. at 25% of the 1000 hr qualification pressure

4. Test data points define the basic envelope that is scaled back to the design envelope by the pressure ratios.

5. If the shape of the envelope for both flanges are equivalent these shapes may be scaled to other diameters and pressure classes using the scaling rules.

Typical flange combined load test set-up

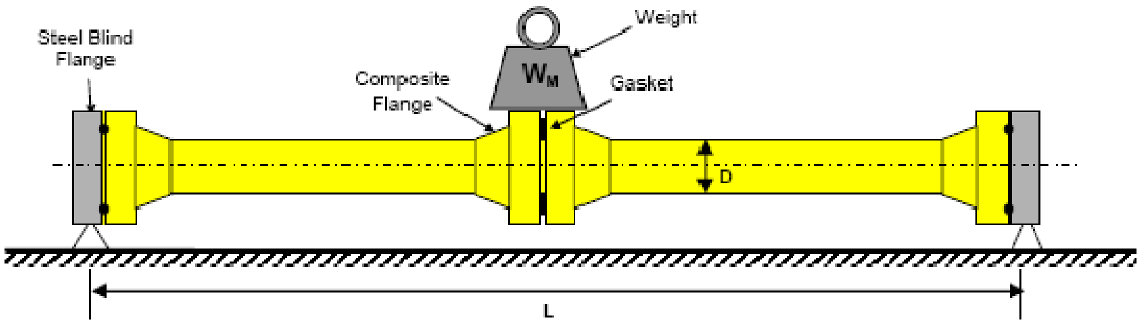

Figure 5; Sample arrangement for combined load testing
(bending moment & internal pressure, additional moment added by weights)

Figure 6; Example; Combined load testing on DN250 PN12.5 Flanged Joint
(bending moment & internal pressure, additional moment added by weights)

Test results

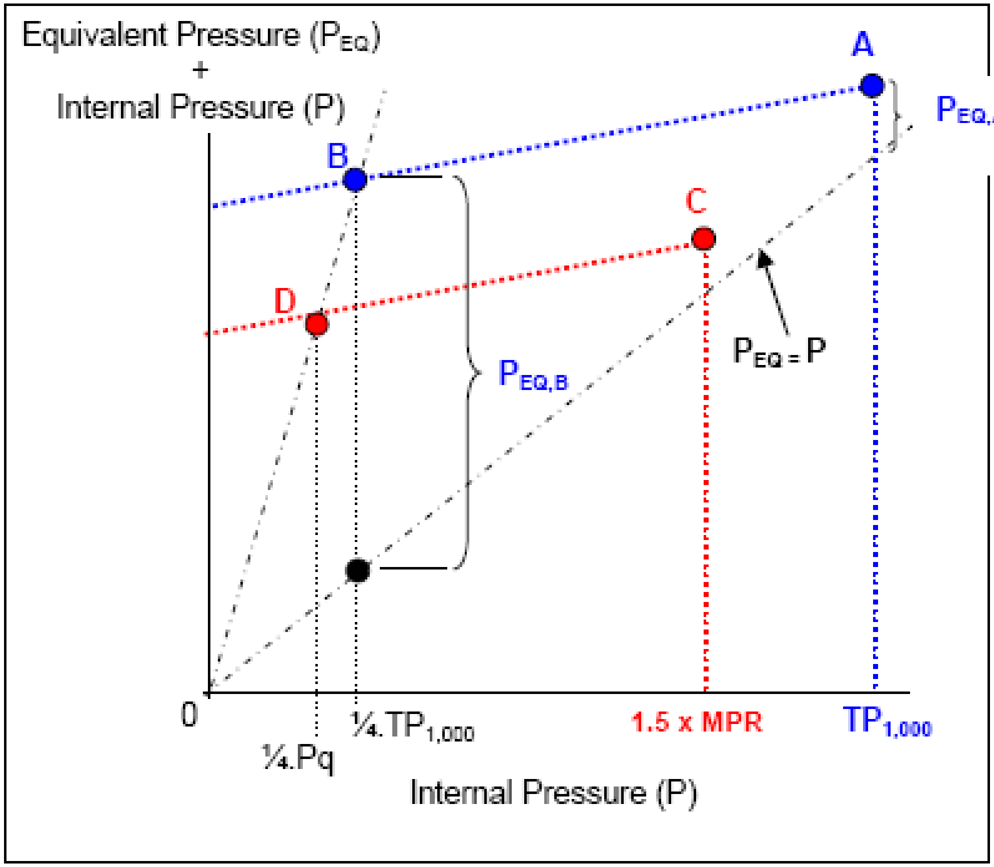

Figure 7; Derivation of long term flange envelope
(Based on Combined Load Testing)

Flange design envelope (conform ISO 14692 revised)

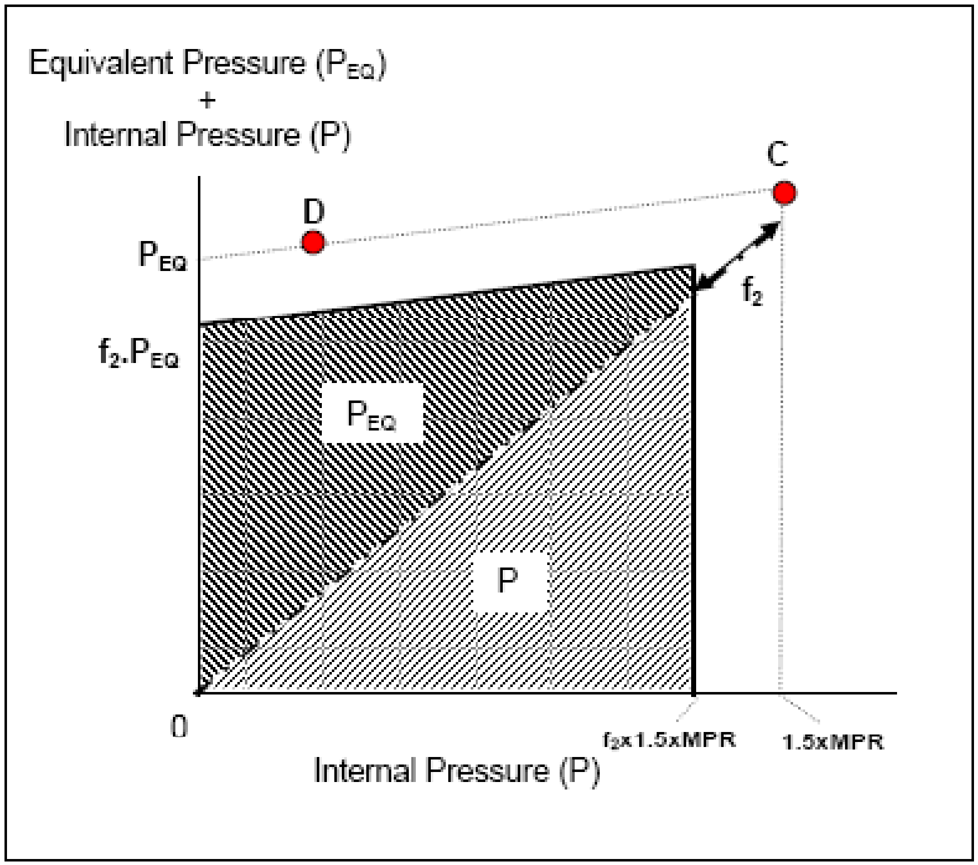

Figure 8; Flange Design Envelope, scaled down as function of f_2.

Default f2 values.

Table 2: Default values for f2 as recommended in ISO14692

Loading Type	Load duration	f2	Example of Loading Type
Occasional	Short-term	0.89	Hydro test
Sustained, including thermal loads	Long-term	0.83	Self-mass plus thermal expansion
Sustained, excluding thermal loads	Long-term	0.67	Self-mass

Thank you