APPENDIX A: ALTERNATE GRAPHICAL SOLUTION

A: PRELIMINARY

Alternatively, a Force-Deformation plot can be also used instead of the Resultant (W) vs. Effective Load (W_e). In Fig. A1 on the right, the clamped components are shown to the left of the Force-axis, while the bolt is to the right; The slope of each load line equals the stiffness of the corresponding member.

Fig. A1

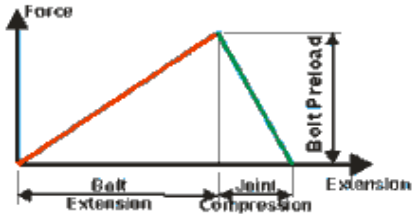

Fig. A2

If the compression line in Fig. A1 is shifted to the right, we will construct the familiar bolted joint triangle as shown in Fig. A2. It is a triangle since the bolt and the clamped parts are under the same amount of force; This force we call the "bolt pre-load", W_i.

When the joint is subjected to an external force, W_e, that tends to increase the bolt tension to W, the resulting response is shown in Fig. A3. From this figure, it is straightforward to derive Eq. 3.

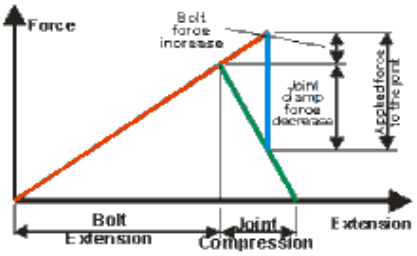

Fig. A3

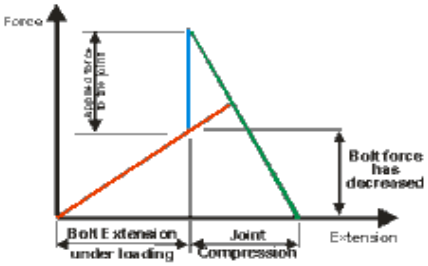

Fig. A4

On the other hand, when the joint is subjected to an external force that tends to increase the joint compression the resulting response is shown in Fig. A4. Notice how the bolt unloads some of its initial preload. This is the case in the warm vessel.

B: COLD VESSEL OUTER BOLTS

Using the values calculated earlier, we can construct a graphical solution for the outer bolts as follows:

$W_i := 50$ < -- Preload, kN

$K_b := 447.5$ < -- bolt stiffness, kN/mm

$K_j := 1411$ < -- joint stiffness, kN/mm

$\delta_1 := \frac{W_i}{K_b}$, or $\delta_1 = 0.112$ < -- initial bolt extension, mm

$\delta_2 := \frac{W_i}{K_j}$, or $\delta_2 = 0.035$ < -- initial joint compression, mm

$W := 62$ < -- projected bolt resultant force, kN

$D := \frac{W}{K_b}$, or $D = 0.139$ < -- projected final bolt extension, mm

$G := K_j \cdot \left[\left(\delta_1 + \delta_2 \right) - D \right]$, or $G = 12$ < -- remaining clamping force, kN

$W_e := W - G$, or $W_e = 50$ < -- applied effective force, kN

Define the following functions for plotting:

$x := 0, .05 .. .15$ < -- horizontal axis, mm

$C(x) := W$ $f(x) := K_b \cdot x$ $g(x) := -K_j \cdot \left(x - \delta_1 - \delta_2 \right)$

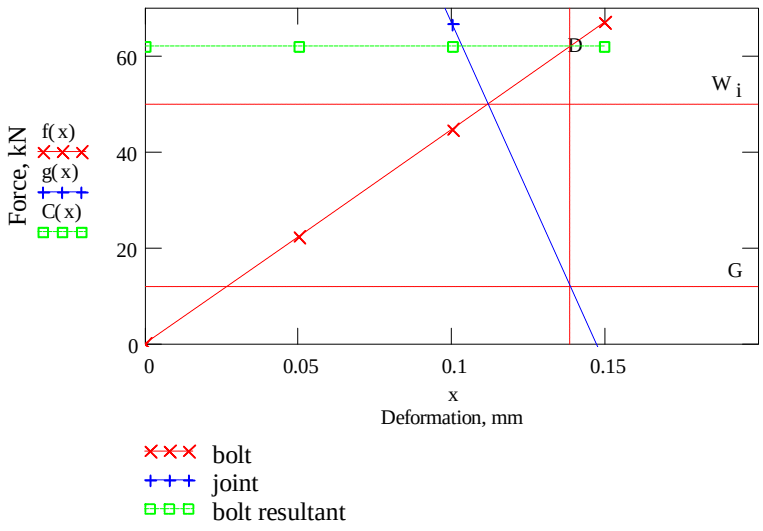

Fig. A5: Force vs. Deformation

C: COLD VESSEL INNER BOLTS

Using the values calculated earlier, we can construct a graphical solution for the outer bolts as follows:

$W_i := 50$ < -- Preload, kN

$K_b := 377.3$ < -- bolt stiffness, kN/mm

$K_j := 1006$ < -- joint stiffness, kN/mm

$\delta_1 := \frac{W_i}{K_b}$, or $\delta_1 = 0.133$ < -- initial bolt extension, mm

$\delta_2 := \frac{W_i}{K_j}$, or $\delta_2 = 0.05$ < -- initial joint compression, mm

$W := 64$ < -- projected bolt resultant force, kN

$D := \frac{W}{K_b}$, or $D = 0.17$ < -- projected final bolt extension, mm

$G := K_j \cdot \left[\left(\delta_1 + \delta_2 \right) - D \right]$, or $G = 13$ < -- remaining clamping force, kN

$W_e := W - G$, or $W_e = 51$ < -- applied effective force, kN

Define the following functions for plotting:

$x := 0, .05 .. .3$ < -- horizontal axis, mm

$C(x) := W$ $f(x) := K_b \cdot x$ $g(x) := -K_j \cdot \left(x - \delta_1 - \delta_2 \right)$

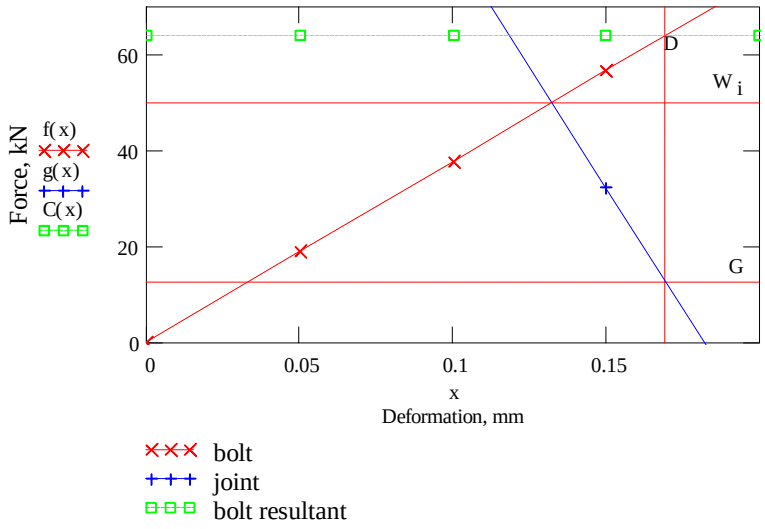

Fig. A6: Force vs. Deformation

D: COLD VESSEL CENTRAL BOLTS

Using the values calculated earlier, we can construct a graphical solution for the outer bolts as follows:

$W_i := 78$ < -- Preload, kN

$K_b := 345.7$ < -- bolt stiffness, kN/mm

$K_j := 980$ < -- joint stiffness, kN/mm

$\delta_1 := \frac{W_i}{K_b}$, or $\delta_1 = 0.226$ < -- initial bolt extension, mm

$\delta_2 := \frac{W_i}{K_j}$, or $\delta_2 = 0.08$ < -- initial joint compression, mm

$W := 79.7$ < -- projected bolt resultant force, kN

$D := \frac{W}{K_b}$, or $D = 0.231$ < -- projected final bolt extension, mm

$G := K_j \cdot \left[\left(\delta_1 + \delta_2 \right) - D \right]$, or $G = 73$ < -- remaining clamping force, kN

$W_e := W - G$, or $W_e = 6.5$ < -- applied effective force, kN

Define the following functions for plotting:

$x := 0, .05 .. .35$ < -- horizontal axis, mm

$C(x) := W$ $f(x) := K_b \cdot x$ $g(x) := -K_j \cdot \left(x - \delta_1 - \delta_2 \right)$

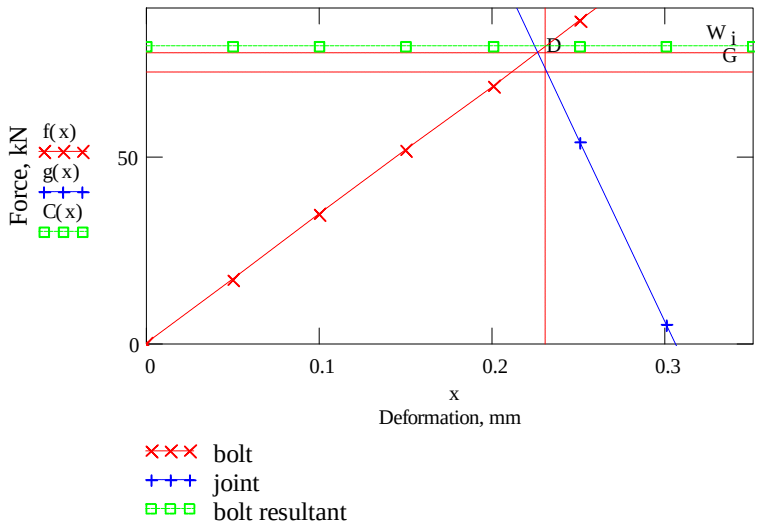

Fig. A7: Force vs. Deformation