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A BEND THICKNESS SENSITIVITY STUDY OF CANDU FEEDER PIPING

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ABSTRACT

In CANDU reactors, feeder bends close to the connection at the fuel channel may be subjected to the highest Flow Accelerated Corrosion (FAC) and stresses. Feeder pipe stress analysis is crucial in the life extension of aging CANDU plants. Typical feeder pipes are interconnected by upper link plates and spacers. It is well known that the stresses at the bends are sensitive to the local bend thicknesses. It is also known from the authors' study (Li and et al, 2005) that feeder inter linkage effect is significant and cannot be ignored. The field measurement of feeder bend thickness is difficult and may be subjected to uncertainty in accuracy. Hence, it is desirable to know how the stress on a subject feeder could be affected by the bend thickness variation of the neighboring feeders. This effect cannot be evaluated by the traditional "single" feeder model approach. In this paper, the "row" and "combined" models developed in the previous study (Li and et al, 2005), which include the feeder interactions, are used to investigate the sensitivity of bend thickness. A series of random thickness bounded by maximum and minimum measured values were applied to feeders in the model. The results show that an individual feeder is not sensitive to the bend thickness variation of the remaining feeders in the model, but depends primarily on its own bend thickness. The highest stress at a feeder always occurs when the feeder has the smallest possible bend thickness. A minimum acceptable bend thickness for individual feeders can be computed by an iterative computing process. The dependency of field thickness measurement and the amount of required analysis work can be greatly reduced.

Keywords: CANDU, feeder, bend thickness, stress analysis, seismic.

1.0 INTRODUCTION

Feeder pipes carry heavy water to and from the reactor fuel channels to remove the heat produced by the uranium fuel fission. The number of feeder pipes ranges from 760 to 960 for various types of CANDU designs, and they connect the inlet and outlet headers to the reactor core. The feeders for most existing plants are made of SA106 Grade B carbon steel and have a nominal pipe diameter varying from 1.5 inch (38 mm) to 3.5 inch (89 mm). Feeder piping is designed to Class 1 piping requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB and CSA Standard (CAN3-N289.3-M81, 1981).

Feeder wall thickness inspections have shown that higher than anticipated wall thinning occurs in some operating CANDU plants, mainly caused by Flow Accelerated Corrosion - FAC (FAC can be reduced by a minimum chromium content of 0.2 wt% in new designs). Although wall thinning has been observed along the entire length of some outlet feeders, the rate of wall loss is the highest in the region of the close radius bends nearest to the outlet feeder port (Grayloc) of the fuel channels. Wall loss due to FAC, plus

thinning caused by the fabrication procedure (cold bending or hot forming) at some sites, may require to establish a minimum wall thickness profile and to perform stress analysis to demonstrate feeder fitness for service in order to comply with the code and maintain safe operation.

Feeder pipes interact with one another through inter linkage components: link plates at upper hangers and spacers located along the vertical pipe runs. Li and et al (2005) concluded that as a result of the feeder interaction, stress at one feeder could be influenced by the neighboring feeders. The impact is significant under the dynamic loading (seismic) conditions for all configurations (short and long feeders) while it may be negligible under the static loading conditions for certain feeder configurations (short feeders). The inter linkage effects become more apparent when the feeder bend thickness becomes smaller. However, the variability effects of feeder bend thickness were not fully investigated in that paper.

Wall thinning rates vary from feeder to feeder based on variation in hydrodynamic parameters, such as coolant velocity and mass flow rate, as well as pipe geometry. Thus, the bend thickness could have different in-service values for pipes with the same installation thickness. The conventional nominal pipe thickness used at the design stage is no longer valid to perform feeder stress analysis to demonstrate the fitness for service of feeders. Because of feeder interaction effects and continuing thinning, it is ideal to conduct the stress analysis with the “real” feeder bend thickness captured at an instant of time. However, the field measurement of bend thickness is time consuming and difficult to conduct due to confined space and high radiation fields. In order to reduce the dependency on the measurement accuracy and the amount of stress analysis work associated with the large amount of possible “real” thickness combinations, it is necessary to establish a bounding minimum acceptable thickness profile for feeders that can be easily compared with the measured data.

The purpose of this study is to investigate the degree to which the neighboring feeder thickness variation could change a subject feeder stress through the feeder to feeder interaction. If the stress on a feeder is affected only by the presence of the connected feeders, but is insensitive to their thickness variation, the stress analysis and the measurement work should be more focused on the subject feeders than on a much larger population of surrounding feeders. Thus, significant cost savings associated with field measurements and analysis work can be achieved.

2.0 FEEDER PIPING MODELS

A typical CANDU reactor may contain from 760 to 960 feeder pipes located in 4 separate quadrants of the heat transport (HT) system. The layout of feeders, shown in Figure 1, is briefly described in this section, while its details are presented in (Li and et al, 2005).

Each feeder piping model begins at the header nozzle and ends at the lower connection to the Grayloc. The Grayloc is a metal to metal seal fitting which connects the feeder pipes to the fuel channels. The two feeder bends adjacent to the Grayloc are close radius bends because of the limited space at the reactor face.

Two types of feeder piping models were developed based on their geometric characteristics:

(i) “Short” feeders are connected to the inboard halves of the HT headers. These feeders serve the upper half of the reactor core. They are connected by link plates in a row and they have only one vertical support along the feeder length. The short feeders in a particular row interact with one another through “link plates” at the rigid hanger locations. The number of feeders in each piping model ranges from a minimum of 2 to a maximum of 12. A typical short feeder piping model is shown in Figure 2.

(ii) “Long” feeders are connected to the outboard halves of the HT headers. These feeders serve the lower half of the reactor core. Not only they are connected by link plates in a row but they also interact with neighboring feeders through spacers. There are two vertical supports along the length of the feeder pipes. Up to 127 inlet and outlet feeders may be contained in one piping model, as shown in Figure 3.

Inter linkage - link plates and spacers (non-piping components) are included in the feeder models using bar elements. The feeder piping model is developed using the in-house piping stress analysis computer program STANPIPES. The program converts the inputs to linear MSC/NASTRAN (V68, 2001) finite

element (beam) models and post-processes the results to check for compliance with the requirements of ASME NB-3650 and CSA Standard CAN3-N289.3 (1981).

3.0 FEEDER BEND THICKNESS MODELLING

The entire length of feeder pipes is fabricated from carbon steel pipe. The feeder bends near the Grayloc are mostly fabricated by cold or warm bending. The extrados of the bends undergo thinning during the fabrication bending process, reducing for example, the nominal 7.01 mm wall of the 2.5" SCH 80 piping to approximately 6.1 mm. The minimum acceptable thickness based on pressure requirement (NB-3641) is 3.333 mm for a 2 ½" feeder at a typical design pressure.

A typical schematic illustration of a feeder bend is shown in Figure 4. It has a thickness variation around the circumference due to the fabrication bending and FAC. The bend gets thicker at the intrados but thinner at the extrados. This effect is most pronounced at the center of a bend. The circumference thickness becomes uniform at both ends of the bend and has the same value as the connecting straight pipe. In this study, the feeder pipes, including bends, are modeled using beam elements with uniform thickness.

3.1 Nominal Thickness - t_{nom}

The size and thickness of feeder pipes including bends are manufactured according to ASME/ANSI B36.10 in most CANDU plants. The nominal thicknesses of 2.0" and 2.5 " bend used in this study are listed in Table 1, and considered as the upper bound thicknesses in the study.

3.2 Pressure Based Minimum Thickness - t_{pmin}

The minimum thickness of pipe wall required for design pressure is calculated from NB-3641. It is considered as the lowest bounding uniform thicknesses of feeder bends in this study.

$$t_{\text{pmin}} = \frac{PD_o}{2(S_m + Py)} \qquad \text{Equation (1) in NB-3641}$$

The outlet feeder design pressure (P) used in the study is 11.275 MPa. The other symbols are well known and do not need to be defined here. The values of t_{pmin} for two sizes of outlet feeder are calculated and listed in Table 1.

Table 1 Minimum Thickness of Pipe Wall Required for Design Pressure

Feeder Type	Nominal diameter	Outside diameter	Nominal thickness	Design pressure	Design temperature	Allowable stress	Minimum thickness
Outlet	D (in)	D_o (mm)	t_{nom} (mm)	P (MPa)	C^o	S_m (MPa)	t_{pmin} (mm)
	2.5	73.03	7.010	11.275	318	119	3.333
	2	60.33	5.537				2.753

3.3 Measured Thickness

Ultrasonic inspection devices are usually employed to measure the feeder piping circumferential wall thickness. Measurements can be taken along the outside of feeder beyond the first two critical bends close to the Grayloc. As expected, the measured minimum thickness (t_{mea_min}) is mostly located at the extrados and the maximum thickness (t_{mea_max}) is at the intrados region. The averaged measured thickness is calculated from the multiple circumferential and axial points along the pipe bend. Measurements have indicated that the 2nd bend from the Grayloc (bend 2) thickness is closely associated with the thickness of the 1st bend from the Grayloc (bend 1). In this study, bend 2 thickness is determined by the bend 1 thickness according to the length of the straight pipe between the two bends, as indicated in Figure 4.

1) For straight pipe length ≤ 150 mm, bend 2 thickness = bend 1 thickness
2) For straight pipe length > 150 mm, bend 2 thickness = 1.09*bend 1 thickness

The above two thicknesses are considered as the lower and upper limits for the "real" bend thickness values by taking account of the measurement uncertainty. Hence, in order to account for the bend thickness uncertainty on feeder stress, the random thickness of the bends is introduced in the next section.

3.4 Random Thickness

As described above, the "real" bend thickness of a feeder can only vary between the two limits (t_{mea_min} and t_{mea_max}). A series of random thicknesses were created using the following formula:

$$t_{rand} = t_{mea\_min} + (t_{mea\_max} - t_{mea\_min}) \cdot \text{rand}() \qquad \text{random number generator} \quad 0 \le \text{rand}() \le 1.0$$

The random number with uniform distribution was created by the random generator in Unix. The random number samples are uniformly distributed between 0.0 and 1.0, as shown in Figure 5. The uniformity of the random number is also verified by its closeness to the theoretical probability value in the specified intervals, as shown in Table 2.

TABLE 2 Probability of Appearance in Specific Intervals and Theoretical Values

Probability in Specific Intervals	Probability	Theoretical values (Moore, 2005)
$P(0.3 \le x \le 0.7)$	0.403	0.40
$P(x \le 0.5)$	0.505	0.50
$P(x > 0.8)$	0.192	0.20

There are total 10 sets of bend thickness used in this thickness sensitivity study: 5 sets of random thickness (t_{rand_i}, i=1,2,…5), the maximum (t_{mea_max}) and minimum (t_{mea_min}) measured thicknesses which bound the above random thicknesses, the nominal thickness (t_{nom}), the pressure based minimum thickness (t_{pmin}), and the lowest value (t_{MEA_MIN}) of the entire sample of individual t_{mea_min} of two size feeders (2.5" and 2.0"). The different cases are summarized in Table 3. The thickness along the rest of the feeder length is modeled as nominal thickness.

Table 3 Ten Sets of Thickness Data Used in the Study

Case No.	Thickness Type	Symbol	Note
1	Nominal Thickness	t_{nom}	as per ASME/ANSI B36.10
2	Random thickness set 1	t_{rand_1}	as per the definition in Section 3.4 $t_{mea\_min} < t_{rand\_i} < t_{mea\_max}$
3	Random thickness set 2	t_{rand_2}	
4	Random thickness set 3	t_{rand_3}	
5	Random thickness set 4	t_{rand_4}	
6	Random thickness set 5	t_{rand_5}	
7	Measured Minimum overall	t_{MEA_MIN}	minimum of $(t_{mea\_min})_{i=1 \text{ to } 65}$, the overall minimum measured value of individual bend 1 thickness of all (65) outlet feeders (2 sizes)
8	Pressure based minimum	t_{pmin}	as per NB-3641
9	Measured maximum	t_{mea_max}	measured maximum thickness at bend 1 of a feeder
10	Measured minimum	t_{mea_min}	measured minimum thickness at bend 1 of a feeder

4.0 ANALYSIS RESULTS

The two most critical stress limits in NB-3650, Equation (9) and (10), are used in this study to compare the bend thickness effects on stress. Code Equation (9) governs the primary stress and is given as:

$$B_1 \frac{PD_o}{2t} + B_2 \frac{D_o}{2I} M_i \le 1.5 S_m \qquad \text{Equation (9) in NB-3650}$$

Code Equation (10) governs the primary plus secondary stress intensity range and is given as:

$$C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + C_3 E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \le 3S_m \qquad \text{Equation (10) in NB - 3650}$$

where B and C are primary and secondary stress indices. The Level A and B loads include pressure, deadweight and multiple thermal transients. The Level C loads, according to the CSA standard (1981), include internal pressure variation, deadweight, seismic anchor movement and seismic inertia loads. In this particular study, the seismic acceleration response spectrum method was used in the short feeder analysis, while the acceleration response time history method was used in the long feeder analysis.

With the exception of deadweight load, the highest stress on a feeder consistently occurs at the bends close to the Grayloc, especially when the bend thicknesses are smaller than nominal values. Only the highest stress at each feeder is presented in the following sub-sections to demonstrate the sensitivity effects of bend thickness. In the case of Level A&B Equation (9) stress, the associated loadings are internal pressure and deadweight. Because the hanger carries most of the feeder weight, the highest stress mostly occurs at the upper rigid hanger location (B_1 is very small at bends). However, when the bend thickness approaches the pressure based minimum value, the highest stress could occur at the bends near the Grayloc.

4.1 Short Feeders

One of the short feeder row models (12 feeders) was arbitrarily chosen to determine the effects of bend thickness. In this row, the nominal diameter at bends close to the Grayloc is 2.5" for 11 feeders, and 2.0" diameter for 1 feeder. The bend 1 thicknesses used in the study are plotted in Figure 6. The corresponding bend 2 thicknesses are calculated using the correlation discussed in Section 3.3.

It was shown by Li and et al (2005) that interaction effects among the "short" feeders are negligible for Level A&B loadings. Therefore, the stress at bends in a feeder should not be sensitive to the variation in thickness of the neighboring feeders. Equation (10) stress for Level A&B loading is shown in Figure 7. The highest Equation (10) stresses at bends vs. bend thickness for the 12 feeders in the model are shown in Figure 8 for Level A&B loading. The highest stress at bends for each feeder increases almost linearly with the decrease of its bend thickness.

The internal pressure change, deadweight and seismic inertia loads are included in Equation (9) stress calculations under Level C Conditions. The Equation (9) stress for Level C is shown in Figure 9. The highest stress on each feeder for the 5 sets of random thickness is bounded by the stress corresponding to the measured maximum and measured minimum thicknesses.

The seismic inertia and seismic anchor movement loads (range) are included in Equation (10) stress calculation under Level C Conditions. The results are shown in Figure 10. Again, the highest stress on each feeder for the 5 random thickness sets is bounded by those corresponding to the measured minimum and measured maximum thicknesses.

The highest stresses at bends vs. bend thickness for the 12 short feeders in the model are shown in Figures 11 and 12 under Level C loading. The associated stresses increase monotonically with the reduction of bend thickness. Compared to Figure 8 for Level A&B loading, the highest stresses at bends under Level C loading becomes more close to each other for the same thickness. This implies that feeder strong interaction under the dynamic loading condition.

The results above demonstrate that a bounding minimum acceptable feeder thickness can be established for individual feeders without needing to be concerned about the possible variation in thickness of the interlinked neighboring feeders. Using an iterative process, the minimum acceptable feeder thickness profile could be obtained by progressively reducing bend thickness from the nominal values, or increasing from the pressure based minimum values, until all feeders comply with the code in the corresponding stress analyses. Each feeder may have different minimum acceptable wall thickness at the bends because of the variation in feeder size, layout, bend configuration and loading etc. The feeder fitness for service can be completed by comparing the measured thickness to the defined the minimum acceptable thickness profile, instead of conducting analyses on the measured data. Thus a large amount stress analysis work, to determine allowable thicknesses at discrete instance of time, to account for variation in neighboring thickness, can be avoided.

In order to further demonstrate the affect of neighboring feeder thickness variation on the stress of a subject feeder, one feeder (F08W) was arbitrarily chosen and its bend thickness at t_{mea_min} (4.69 mm) was fixed, while the bend thicknesses at other feeders were changed by using the same data in Table 3. This is a repetition of the above analyses with the exception of feeder F08W thickness remaining constant. The highest stress at F08W in the study is then compared to the reference case (Case no. 10 in Table 3), i.e. all feeders are at measured minimum thickness (t_{mea_min}). There is virtually no change in the highest stress at feeder F08W bends when the other 11 feeders in the model having varying thickness from the 5 random sets (t_{rand_i}), measured maximum (t_{mea_max}) and the overall measured minimum (t_{MEA_MIN}) thicknesses, as shown in Figure 13. While the rest of the feeders are at the much higher nominal thickness (50% higher for t_{nom} = 7.01 mm of 2.5" feeders, compared to 4.69 mm), the stress on F08W changes less than 1.5%. When the rest of feeders are at the much lower pressure based minimum thickness (29% lower for t_{pmin} = 3.333 mm of 2.5" feeders, compared to 4.69 mm), the stress on F08W changes less than 1.5% for Level A&B loading, and approximately 6% for Level C loading. These results demonstrate that stress on a subject feeder is not sensitive to the bend thickness variation of the neighboring feeders, especially when such variation is in a realistic range, such as between measured minimum (t_{mea_min}) and measured maximum (t_{mea_max}) thicknesses.

4.2 Long feeders

In the long feeder analysis, the "combined" model was created by adding the link plate and spacer models into "row" feeder models. The analysis is carried out for 127 outlet and inlet feeders in the model, which has 6 outlet and 6 inlet feeder rows of feeders of both 2.0" and 2.5" nominal diameters. The bend 1 thicknesses used in the study are shown in Figure 14. The corresponding bend 2 thicknesses are calculated using the correlation discussed in Section 3.3. There are 65 outlet feeders in this model contained in 6 "row" models. In Figure 14, the abscissa axis represents the feeder number and the corresponding row model number. The highest stresses in each of the 6 outlet row models are plotted to show the effects of bend thickness variation. Since wall thinning in inlet feeders is insignificant, thus thicknesses of inlet feeders are kept at the nominal values in this study.

The highest Equation (9) and (10) stresses for Level A&B loadings for the 6 rows at the bends close to the Grayloc are shown in Figure 15, while the stresses for Level C loading are shown in Figure 16. As seen from the above figures, the highest stresses in each row model for the 5 sets of random thicknesses are bounded by the stress corresponding to the measured maximum and measured minimum thicknesses. The stresses for the later two thicknesses are bounded by the stresses corresponding to the nominal and pressure based minimum thicknesses. Like the short feeders, a bounding minimum acceptable feeder thickness can be established for individual long feeders.

Similar to the study done on short feeders, one feeder (S07E) was arbitrarily chosen and its bend thickness at t_{mea_min} (4.78 mm) was kept constant, while the bend thicknesses at other feeders vary by using the nominal (Case no. 1), one random thickness (Case No. 2), and pressure based minimum thickness (Case no. 8), which are considered to be the upper and lower limits of thickness. The highest stress at S07E in the study is then compared to the reference case (Case no. 10), at which all feeders are at measured minimum thickness (t_{mea_min}). As shown in Figure 17, the maximum stress variation on the feeder (S07E) is approximately 5% under Level A&B or Level C loadings, which is corresponding to 50% bend thickness variation of the remaining feeders. Therefore, the stress on a subject long feeder is not sensitive to the thickness variation in the other outlet feeders (64) in the model.

5.0 CONCLUSIONS

The following conclusions can be drawn from this study:

1) As demonstrated in authors' other study on the CANDU feeder piping (Li and et al, 2005), the feeder interacts with each other through the inter linkages. Feeders connected by inter linkages, such as link plates and spacers, must be modeled together. However, the study conducted here indicates that the stress on a particular feeder is not sensitive to the variation in bend thickness of the neighboring feeders. The highest stress on the bend increases almost linearly with the decrease of the bend thickness. In fitness for service of feeders, it is critical to make accurate thickness measurement of the subject feeders and less concerned of neighboring feeders.

2) The highest stress on a feeder is mostly affected by its own bend thickness. The stress associated with any higher thickness is always bounded by the higher stress corresponding to the smaller bend thickness. A minimum acceptable thickness for each feeder can be obtained by an iterative stress analysis procedure. By comparing the minimum acceptable thickness value to the measured data, significant cost saving can be achieved in the feeder fitness for service assessment.

6.0 ACKNOWLEDGEMENT

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Figure 1 A View from a Typical CANDU Reactor Face (showing feeder bends and fuel channels, courtesy of canteach.candu.org)

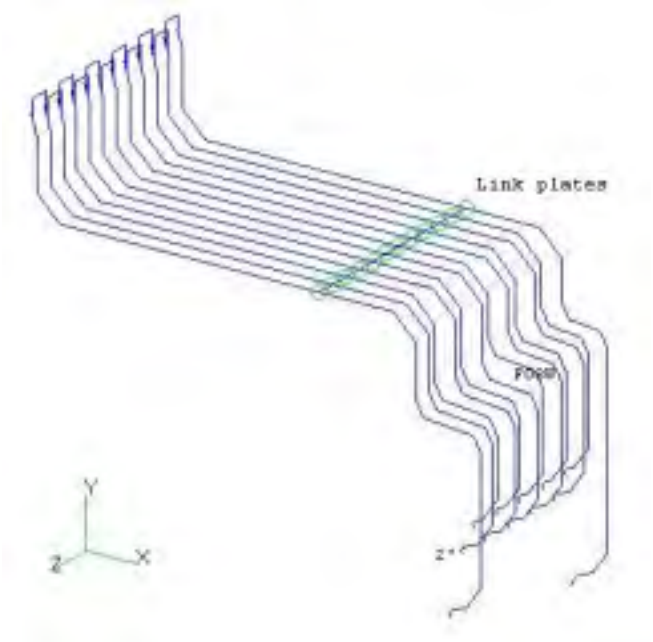

Figure 2 An Isometric View of SHORT Feeder Row Model with Link Plates

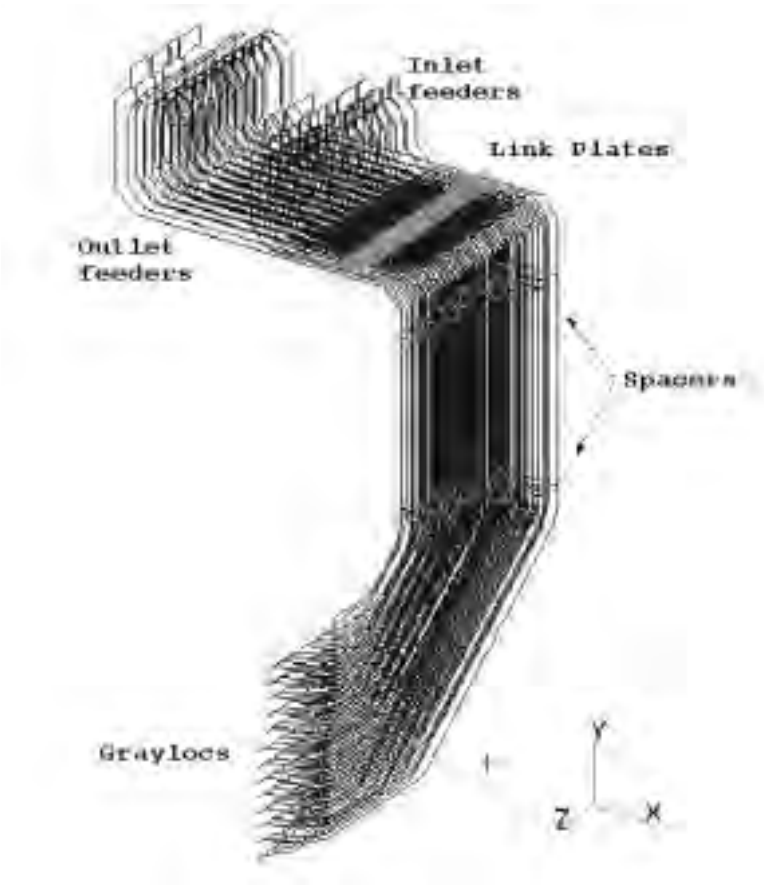

Figure 3 An Isometric View of a Combined LONG Feeder Quadrant Model

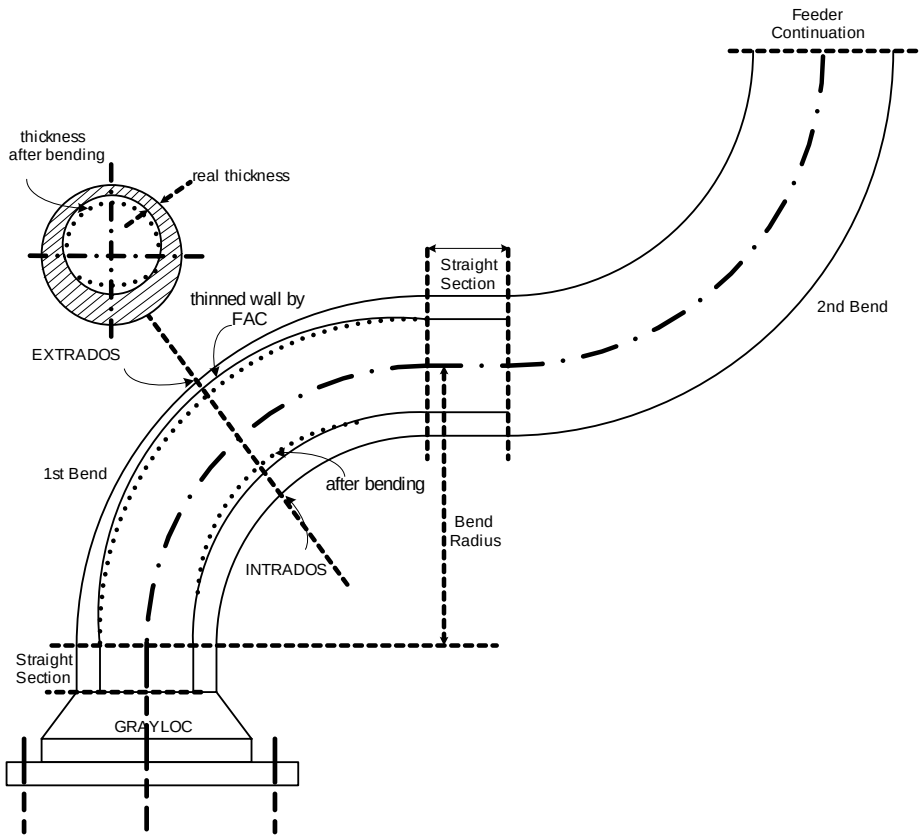

Figure 4 A Schematic Illustration of Geometry of Feeder Bends Close to the Grayloc

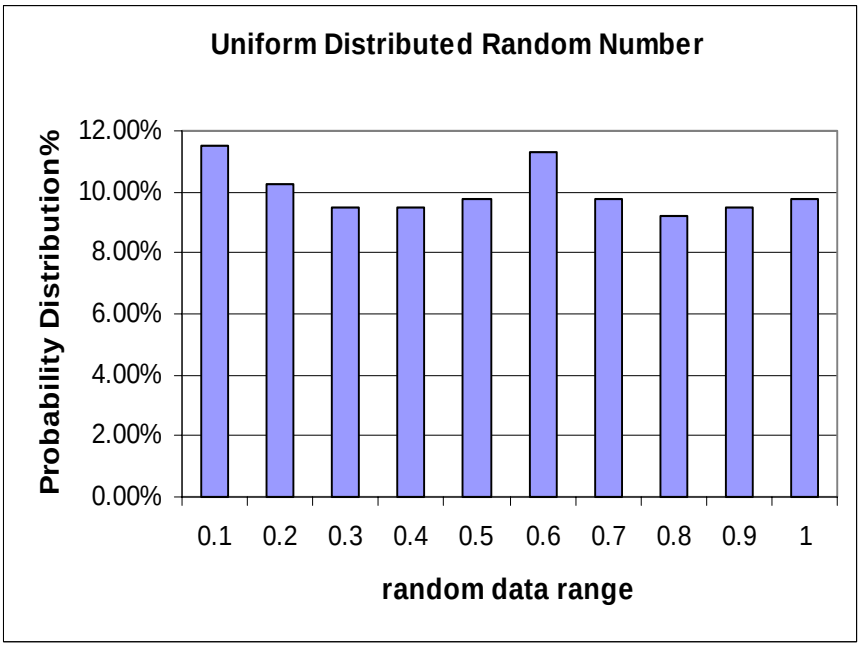

Figure 5 The Uniform Distribution of the Random Number Used in the Study

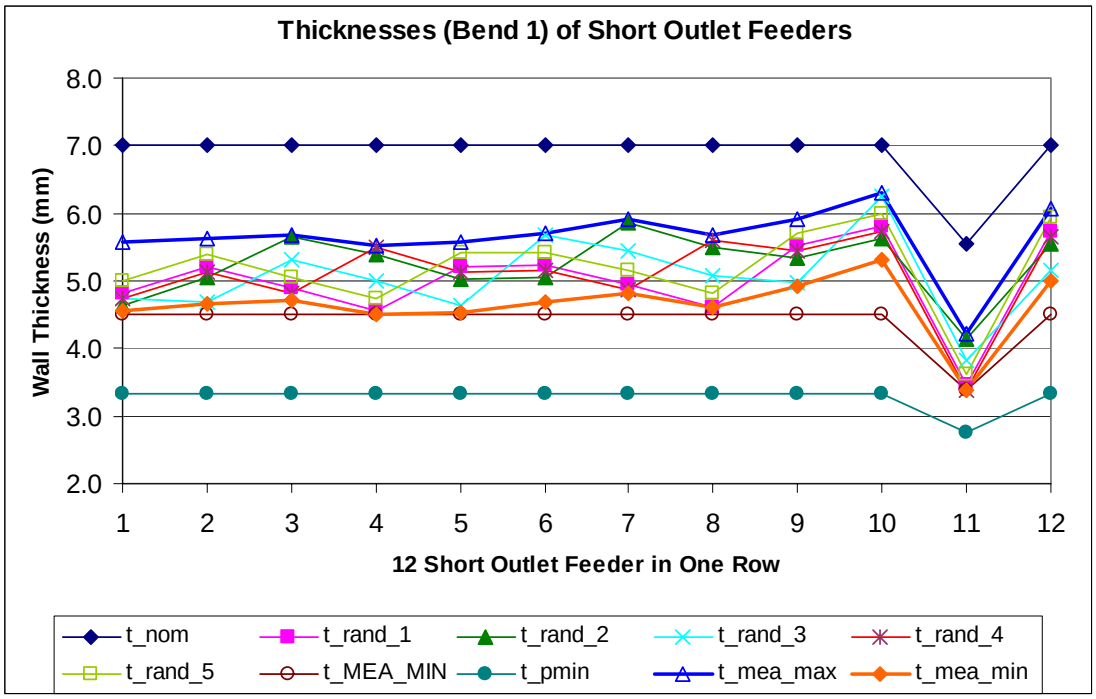

Figure 6 The Uniform Wall Thickness of the 1st Bend Close to the Grayloc Used in Short Feeder Study

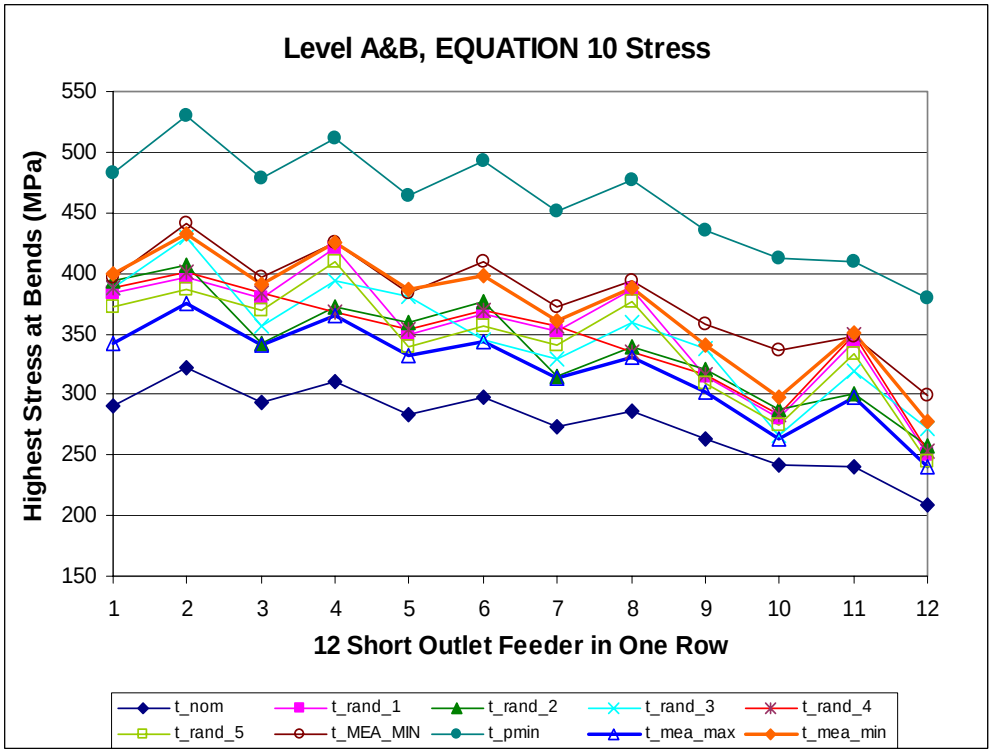

Figure 7 Equation (10) Stress in SHORT Feeders – Under Level A&B Loads

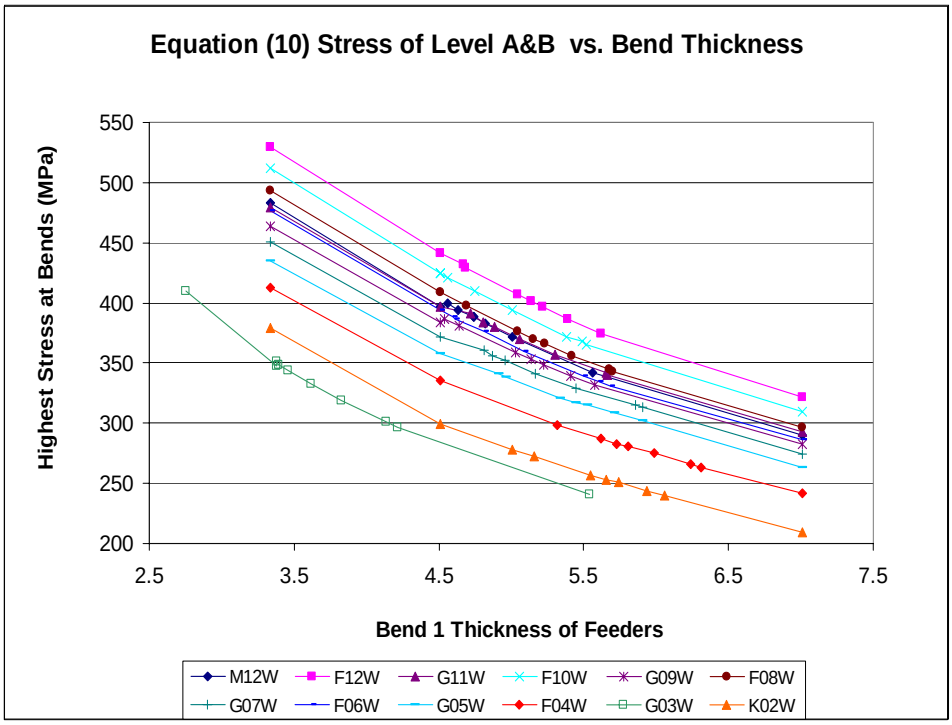

Figure 8 Equation (10) Stress in SHORT Feeders at Bends - Under Level A&B Loads vs. Bend Thickness (legend indicates individual feeder name)

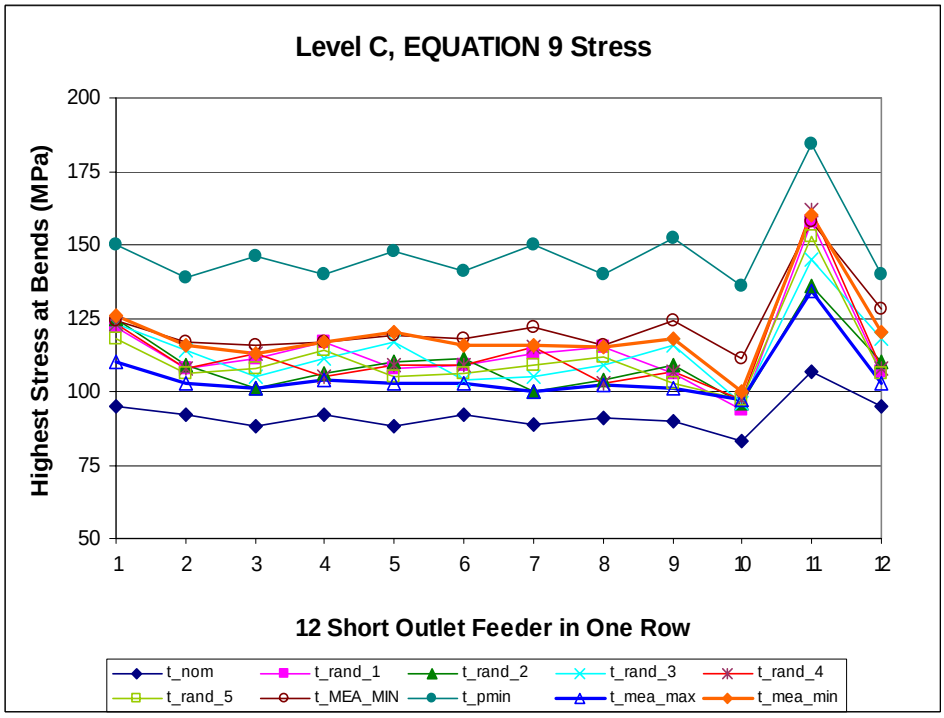

Figure 9 Equation (9) Stress in SHORT Feeders – Under Level C Loads

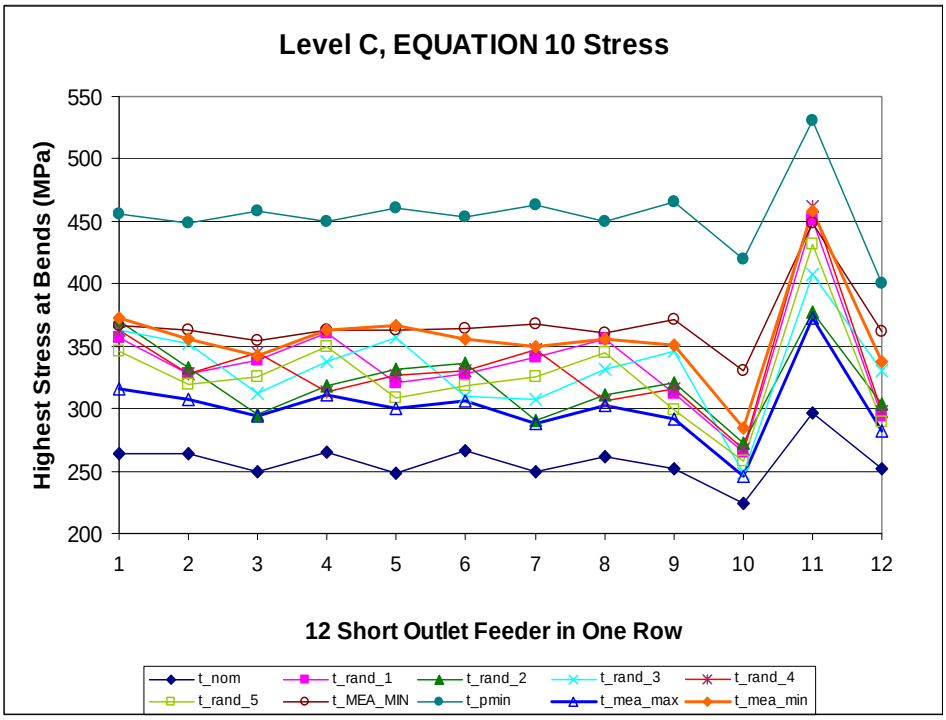

Figure 10 Equation (10) Stress in SHORT Feeders – Under Level C Loads

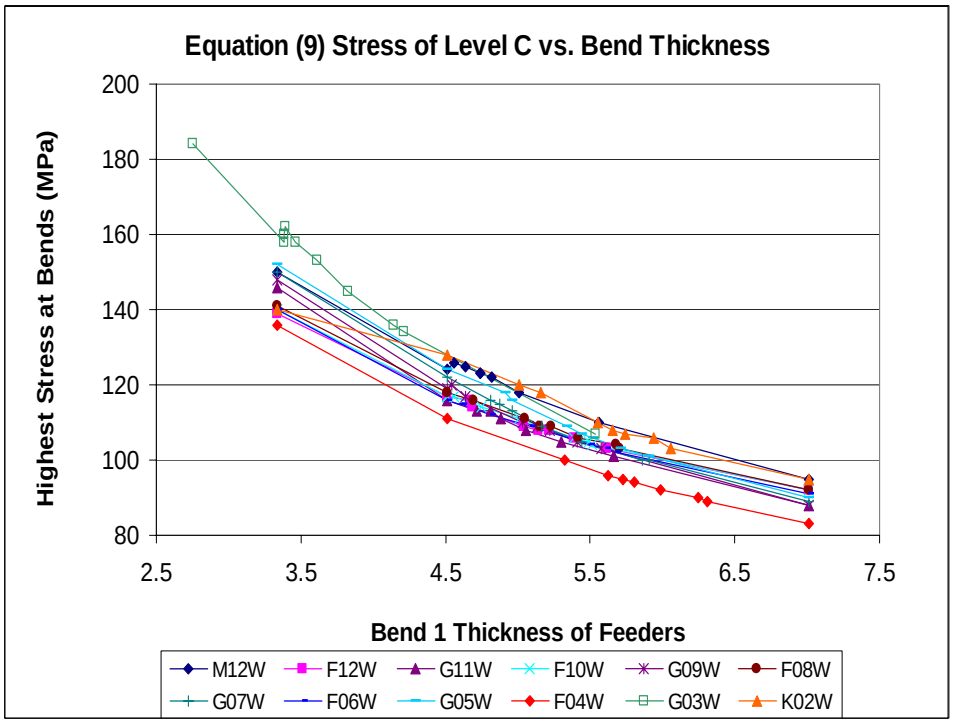

Figure 11 Equation (9) Stress in SHORT Feeders at Bends - Under Level C Loads vs. Bend Thickness

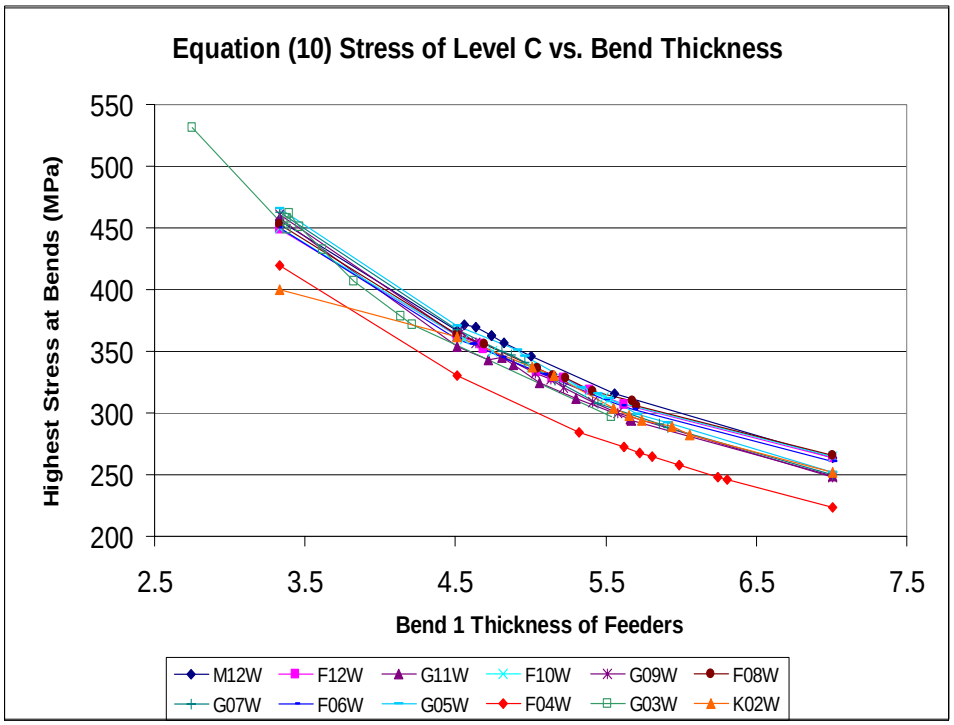

Figure 12 Equation (10) Stress in SHORT Feeders at Bends - Under Level C Loads vs. Bend Thickness

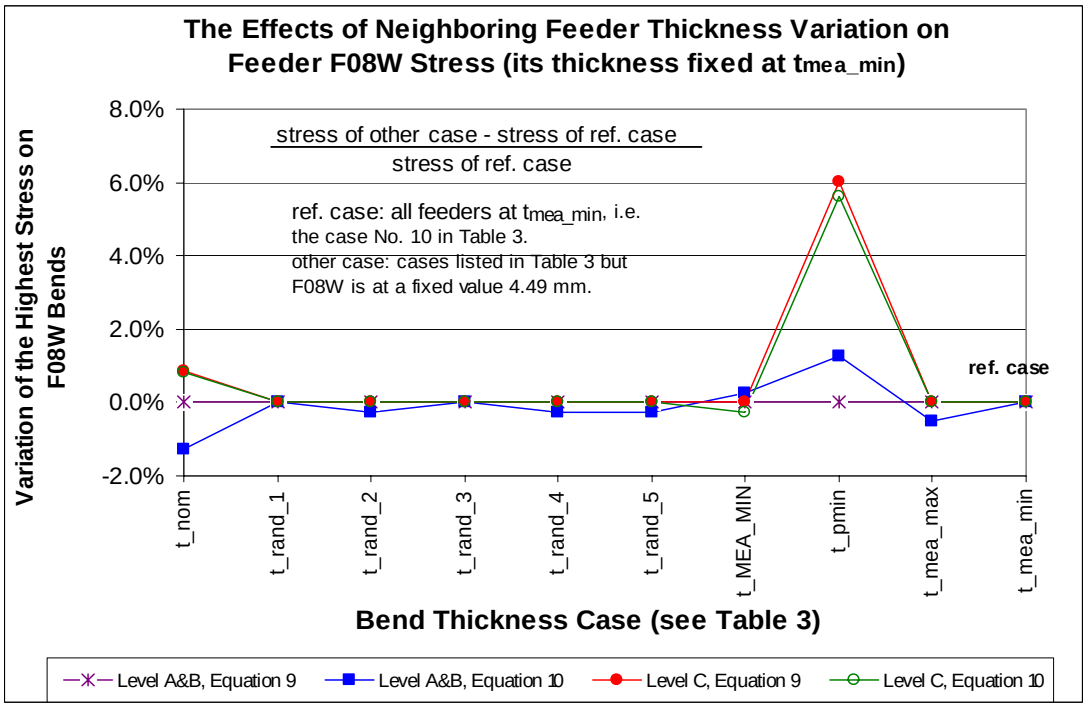

Figure 13 Variation of the Highest Stress on Feeder F08W (thickness fixed at t_{mea_min} = 4.69 mm) While Other Feeders in the Model Using Different Sets of Bend Thickness

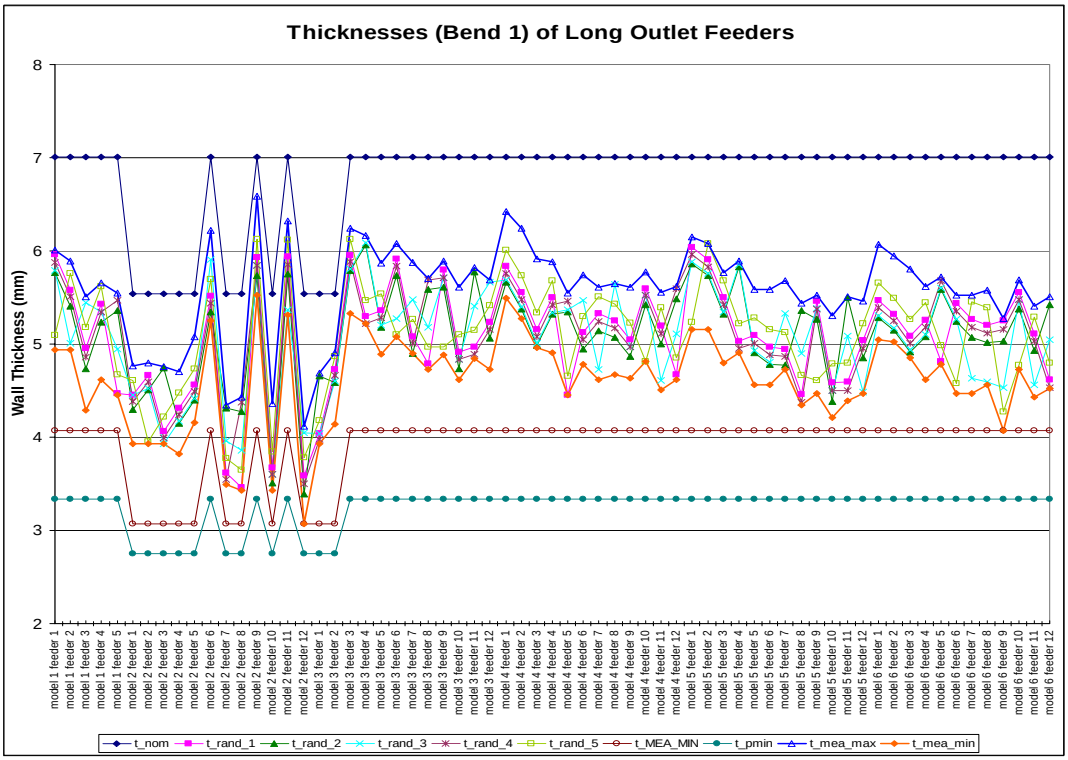

Figure 14 The Uniform Wall Thickness of the 1st Bend Close to the Grayloc Used in Long Feeder Study

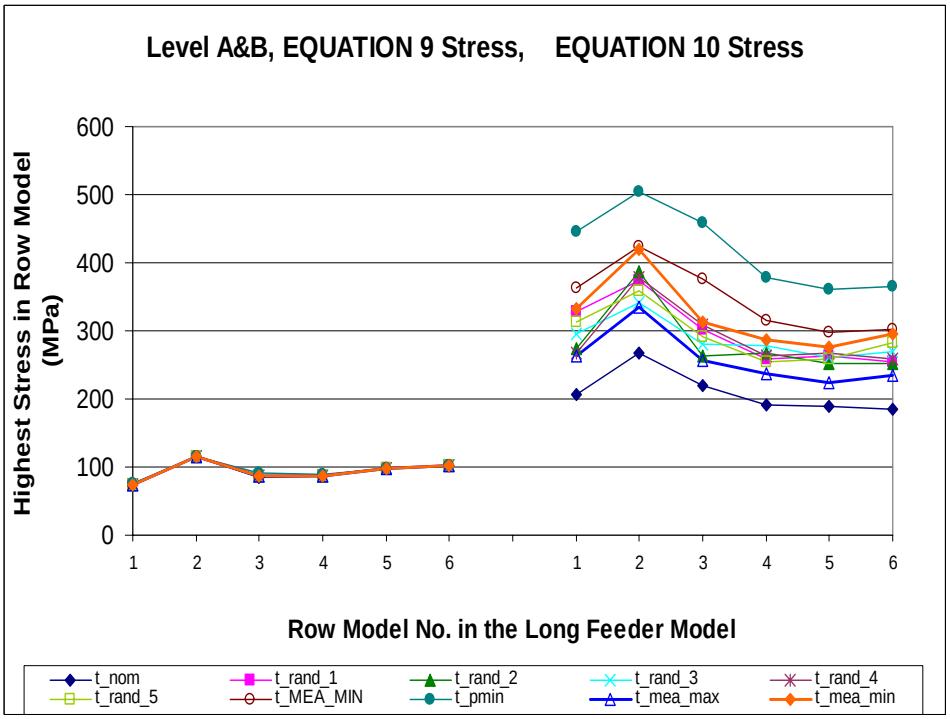

Figure 15 Equation (9) and (10) Stresses in LONG Feeders – Under Level A&B Loads

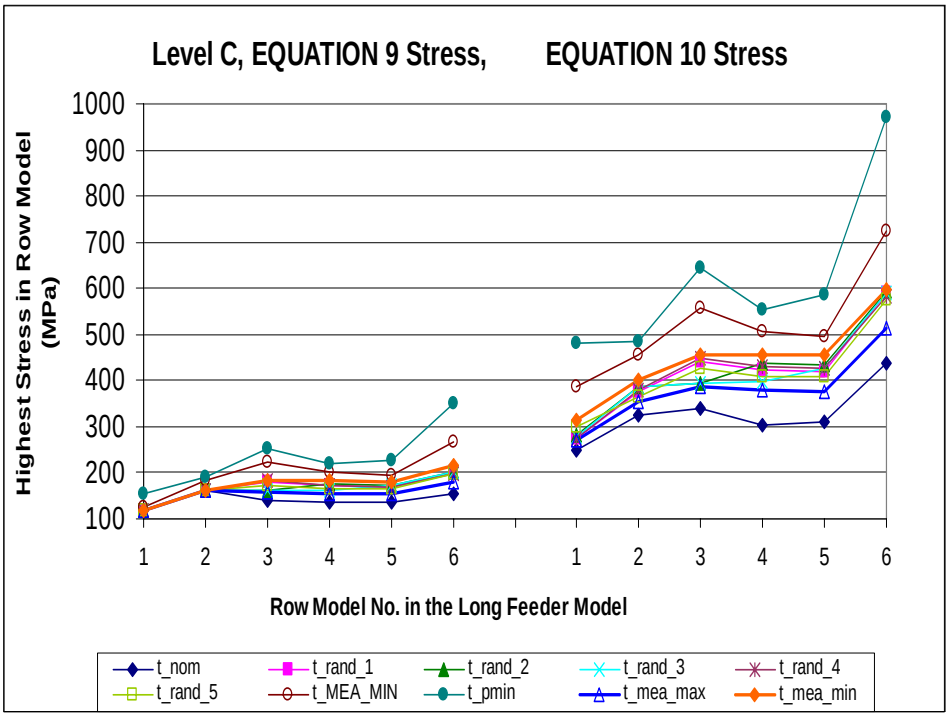

Figure 16 Equation (9) and (10) Stresses in LONG Feeders – Under Level C Loads

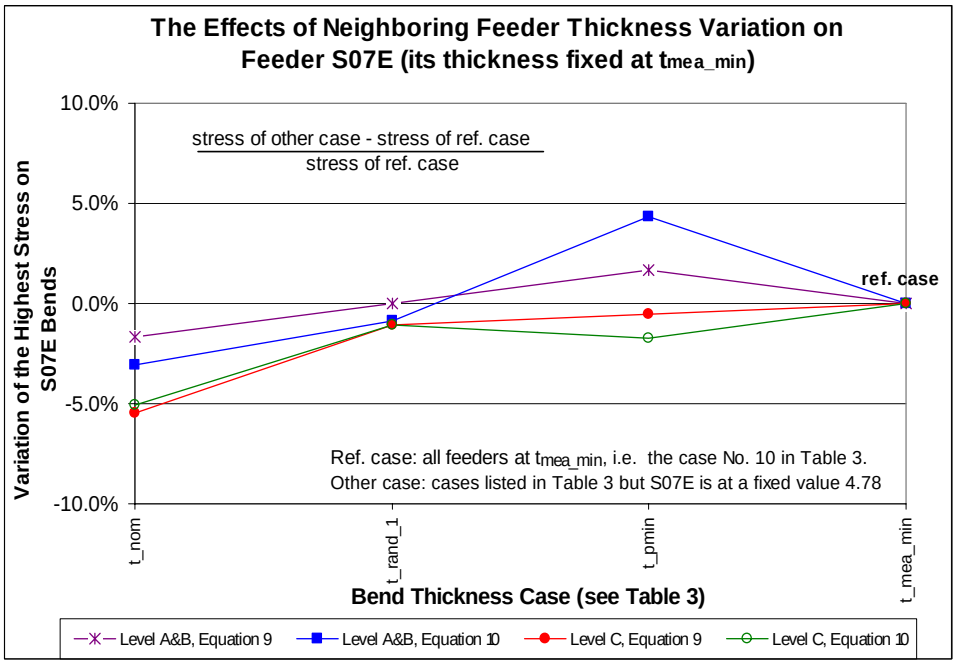

Figure 17 Variation of the Highest Stress on Feeder S07E (thickness fixed at t_{mea_min} = 4.78 mm) While Other Feeders in the Model Using Different Sets of Bend Thickness