GENERIC AND PROFILE SPECIFIC FEEDER STRESS ANALYSIS

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Flow assisted corrosion (FAC) caused wall thinning has been observed on CANDU feeder pipes. Thinning in general occurs in the first two bends near the Grayloc fitting. In a fitness for service analysis of thinned feeders, the inspected or predicted minimum thicknesses are often used in the stress analysis. The determination of the exact location of the thin spot, axially and circumferentially, is dose intensive during inspection.

In view of urgency during an outage to disposition measured thicknesses, two types of stress analysis approaches are developed. Type A analysis, also named here as the "Average-Minimum-Average" or generic approach provides requirements on minimum wall thickness as well as average wall thickness. The required minimum wall thickness is not location specific and can reside anywhere within the first two bends. It provides great flexibility to disposition feeders with either general or local thinning. On the other hand, Type B analysis is conducted with the exact thickness profile. Type B analysis is performed on feeders which do not pass Type A analysis.

The two approaches have been demonstrated in Darlington feeders, where the majority (413 out of 480) of feeders has Type A requirements, while 67 out of 480 have Type B requirements. Type A requirements provide a greater flexibility to disposition local thinning on feeder pipes.

1.0 INTRODUCTION

In CANDU nuclear power plant, feeder pipes carry heavy water to and from the reactor fuel channels to remove heat produced by the fission of uranium fuel. The feeder pipes connect the inlet and outlet headers to the reactor core. The number of feeder pipes is in the range of 760 to 960 for various types of CANDU designs. The feeders are made of SA106 Grade B carbon steel and range from 1.5 inch (38 mm) to 3.5 inch (89 mm) nominal pipe diameter, with lengths from 20 feet (6.1 m) to 60 feet (18.3 m). Feeder piping is designed to Class 1 piping requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB and CSA Standards. A typical feeder has several bends between a header and a fuel channel. In general, bends closest to the fuel channel connections represent the most critically stressed sections of feeder pipes. Severe wall loss due to FAC has been found in CANDU stations, the wall thickness reduction could be as high as the half of nominal wall values.

In order to avoid or delay costly feeder replacement at Darlington station, feeder piping code compliance analyses have been conducted in various phases in past several years:

"Phase one" – the modeling and analysis were carried out between 2000 and 2002. In that analysis, STANPIPES (**Reference 1**) piping models for all 960 inlet and outlet feeders of a reactor unit with nominal thickness were developed. It was first time industrial effort to model inter-link effects among feeders. A typical inter-linked multi-feeder model is shown in **Figure 1 (Reference 2)**. The required thicknesses for all short and long outlet feeders were determined by using uniform thickness profile at bends. The minimum acceptable uniform thicknesses were obtained iteratively to check code compliance. This approach was the first attempt to establish the acceptable thickness for every Darlington outlet feeder. It is a conservative approach that doesn't account for the reality of non-uniform bend thickness at the cross-section. The non-uniformity is caused by the feeder fabrication process as well as the FAC thinning process.

"Phase two" – from 2003 to 2005. The assessments were carried out on predicted outage thickness. In this phase, the simplified bend thickness profile was developed, which accounts for the thicker wall between cheeks and intrados. The "Average-Minimum-Average" approach in the STANPIPES analysis was developed and implemented for non-uniform thickness profile: the average thickness is used for feeder stiffness and load calculation; the minimum thickness is used for stress index calculation; the average thickness is also used to calculate the moment of inertia for code compliance check.

In this phase, the assessments were conducted on the predicted thicknesses at future planned outages, which were based on inspection results and estimated thinning rate. Predicting future thickness for feeder assessment is a complicated task, and repetitive stress assessments for various outages can consume significant part of piping analysis resources.

"Phase three" – conducted in 2006. In this phase, an acceptable thickness value for each feeder is obtained to meet code compliance. The acceptable thickness is independent of outage or inspection thicknesses. Iterative calculations are conducted to obtain the minimum acceptable thickness profile. In this assessment, the minimum thickness at bends for all feeders is pressure based minimum thickness, but it has different requirements depending on the type of analysis employed on individual feeders. The Generic and Profile Specific approaches are introduced in this assessment. In Generic or Type A analysis, requirements are more flexible: the minimum thickness can be anywhere on bends while maintaining a higher average thickness; In Profile Specific or Type B analysis, the requirement is more restrictive: the actual thickness profile has to be bounded by the given or analyzed thickness profile. The overview of Darlington outlet feeder analysis is summarized in **Figure 2**.

Most local thinning problem in Darlington feeders can be resolved by the generic Type A analysis. It is flexible for the requirement of minimum thickness location - by simply comparing the measured or predicted minimum thickness with the pressure based minimum thickness. More complicated Type B analysis is only required for a small percentage of feeders. Significant reduction in cost, dose, and response time is achieved for feeder fitness for service.

2.0 METHODOLOGY

The stress range in ASME piping code NB-3600 is presented in a general form below.

$$Si(T_{min})*\frac{D_o * M_i(T_{avg})}{2*I(T_{avg})} \qquad (1)$$

where
- Si – stress index (B, C, K)
- D_o – outside diameter of pipe
- M_i – resultant range of moment
- I – moment of inertia

T_{min} – minimum thickness at the bend cross section
T_{avg} – average thickness at the bend cross section

Two types of analysis are developed for feeder fitness for service assessment. Generic thickness profile analysis (Type A); and Profile specific thickness profile analysis (Type B).

2.1 Type A analysis

This analysis is conducted in STANPIPES or other general piping stress analysis software by using "Average-Minimum-Average" (**Reference 3**) approach, i.e. the average thickness (T_{avg}) is used to calculate loads and section modules, while the minimum thickness (T_{pmin}) is used to calculate stress index (B, C and K). In expression (1), $Si(T_{min})$, $M_i(T_{avg})$, $I(T_{avg})$ are taken as functions of minimum and average thicknesses respectively. This approach has been proven to be conservative by comparison made to solid finite element results (**Reference 3**).

The C_2 index is an important parameter in feeder bend stress analysis because it is a measure of the bending stress increase of elbows due to geometry (including pipe and bend radius, wall thickness profile and etc.) in comparison to the straight round pipe. It is commonly known that the value given in ASME code (**Reference 4**) is conservative. In this assessment, the stress indices (C_2, and B_2) for the two pipe bends at the pressure minimum thickness closest to the Grayloc on each outlet feeder are pre-determined by using detailed solid finite element analysis and stored in data base. The C_2 index is dependent on bend characteristics, namely length, angle, pipe and bend radius and etc. In each CANDU station, there are approximately 20 types of feeder bends, whish are far less than the total number of feeders.

Because uniform T_{pmin} is used to calculate C_2 and other stress indices as per code values, thus the minimum thickness can be at any location of the cross-section. The thermal expansion stress is dominated by the overly conservative C_2 calculated from uniform T_{pmin}. There is little effect by increasing the average thickness value. Type A analysis is conducted with a pressure based minimum wall (T_{pmin}) and an average wall thickness of 110% of T_{pmin}.

Type A analysis results provide the Station with a set of required minimum wall thickness and average wall thickness. The required minimum wall thickness is not location specific and can reside anywhere on the circumference along the length of the first two bends, including straight pipe downstream the Grayloc. The average wall thickness of a feeder, evaluated by the Station based on field inspection data, should also be maintained above the required average wall thickness.

2.2 Type B analysis

The analysis is conducted using the combination of STANPIPES on piping models and other commercial software (ANSYS, ABAQUS) on solid finite element models. In solid element model, the detailed thickness profile is defined. For a particular feeder, it could be a specific thickness based on outage inspection results or predicted thickness based on thinning rate. For the broad scope assessment carried out in phase 3 described in Section 1, the simplified thickness profile is used. This thickness profile is defined as such: linearly varying thickness on the extrados region (0 degree to 90 degree and 270 degree to 0 degree, minimum wall at 0 degree) and a uniform value on the intrados/cheek region (90 degree to 270 degree), i.e. T_{pmin} is at the extrados, thickness between intrados and cheeks (T_{int} and T_{cheek}) are constant, as shown in **Figure**

3. From past inspection data, this thickness profile is found to meet well the actual thinned bends for most feeders. The load or thickness profile specific C_2 is calculated and substituted into STANPIPES to evaluate fatigue value, thus the location of thickness profile is precisely defined.

Type B analysis is performed on feeders which do not pass Type A analysis with a pressure based minimum wall and a 110% pressure based average wall thickness. Type B analysis is defined in more detail than Type A and requires more inputs from the Station to validate.

It is not necessary that the measure/predicted minimum thickness is at the extrados location, or the profile is shaped like the simplified profile as long as the measured profile is bounded, see **Figure 4**. However, if the predicted bend thickness is projected to be the pressure based minimum thickness, which is the current limiting factor for feeder operating life, the minimum value of projected thickness profile must be at the extrados if the simplified thickness profile is used.

A schematic of the analysis procedure for Type A and B is shown in **Figure 5**. If a feeder pipe meets code compliance with piping analysis software alone, except pre-determined C_2 and B_2 values, the analysis is a Type A or generic thickness analysis. For higher stressed feeders, typically higher thermal expansion stress for short feeders and higher seismic inertial stress for long feeders, detailed finite element analysis is required to incorporate with conventional piping analysis. Thermal static loads from piping software are input into ”chopped” solid finite element model, which only includes the Grayloc, thinned bends and adjacent pipe sections. The highest membrane plus bending stress is compared to code Equation (12) limit of $3S_m$. Once this limit is met, the equivalent thermal load C_2 value is calculated and input back to piping software to utilize its built-in fatigue calculation capability to calculate the cumulative thermal fatigue values.

For higher stressed long feeders, the solid finite element bend section is generated in ANSYS or ABAQUS and embedded in piping model to simulate seismic inertial effects. The highest membrane plus bending stress is compared to code Equation (13) limit of $3S_m$. Again the equivalent seismic load specific C_2 is calculated and subsequently used in fatigue calculation. The total cumulative usage factor (CUF) from thermal and seismic loads must be below unity.

3.0 DARLINGTON FEEDER ASSESSMENT

The above methodology is carried out in phase 3 of Darlington feeder assessment for all of 480 outlet feeders. It is essential to obtain the minimum acceptable thickness or a generic acceptable thickness for each feeder in order to assess wither or not any feeder could continue in safe service based on outage inspection data. The generic thickness is defined as reduction of the required average thickness in non-uniform thickness profile, characterised by two thicknesses (minimum and average), as close as possible to pressure based minimum thickness. The minimum thicknesses at bend 1 and bend 2 are consistently assumed at pressure based thickness in the iteration process. The average thickness will be at a higher thickness to the extent necessary so that the feeder stresses meet code allowable stresses. The analysis is performed by maintaining the minimum thickness at pressure based minimum thickness value and increasing the average thickness in successive iterations until the feeder stresses meet code allowables.

In general, for short feeders, the thermal expansion stress, i.e. Equation (12) stress, is the limiting factor. For long feeders and a few short feeders, the seismic inertia stress, i.e. Equation (13) stress is the limiting factor. Bend thickness values are also checked to meet other code requirements, including the pressure requirements.

Equation (1) of NB-3640 must be maintained for both straight pipe and bends to prevent catastrophic pipe burst failure. For pipe bends with nominal thickness, Equation (1) check is sufficient because the manufacture tolerance and fabrication process which could produce thicker wall at the bend intrados. For degraded pipe elbows, uniform bend thickness could become one of the postulated scenarios, even extreme unlikely in reality. Preliminary limit load analysis indicates that 10% higher average thickness than the pressure based thickness, or 13% higher intrados thickness than extrados (i.e., $T_{ext} = T_{pmin}$, $T_{avg} = 1.1T_{ext}$ and $T_{int} = 1.13T_{ext}$), shall be sufficient to meet collapse pressure requirement. The field inspection experience consistently shows average bend thickness exceeds more than 25% of measured minimum thickness.

Therefore, the following two criteria of simplified elastic-plastic approach in ASME III are both met in order to obtain the generic relief thickness value for each feeder:

1. Equation (12) of NB-3653.6 stress is less than $3S_m$ for short feeders; Equation (13) of NB-3653.6 stress is less than $3S_m$ for long feeders and a few short feeders;

2. To be conservative in pressure protection, rather required by stress analysis, the average thickness T_{avg} is at least 10% higher than pressure based minimum thickness T_{pmin}.

3. Other code limits are all met.

In order to reduce the number of analysis iterations, only a few bend average thickness iterations were performed for each feeder: 110%T_{pmin}, 115%T_{pmin}, and 120%T_{pmin}, as shown in **Figure 6**. A small number of feeders require the average thickness higher than 120% T_{pmin}. It should be noted through the calculation and iterations, the minimum thickness remain at the value of T_{pmin}, only the bend average thickness increases.

Once a feeder bend thickness meets the code requirements, the feeder thickness for this particular feeder remains unchanged for the next iteration, which is conducted because of other "failed" feeders in the model. A feeder bend thickness sensitivity study (**Reference 5**) has shown that although stresses on a subject feeder are affected by the existence of neighboring feeders through structural interaction, but the stress of the subject feeder is not sensitive to the thickness variation of neighboring feeders. In other words, the acceptable thickness for each individual feeder remains valid despite that actual thicknesses of neighboring feeders may differ from what was used in the analysis.

All other outlet feeder segments, as well as inlet feeders, are considered to be "unthinned", or of nominal thickness.

Positioning Assembly (PA) locking switch of fuel channel is scheduled in the middle of fuel channel or feeder service life. The locking condition, free or fixed, has impact on feeder thermal expansion stress. Feeder experiences higher thermal expansion stress while connected to the free fuel channel end, and lower stress while connected to the fixed end. This impact is only shown on short feeders which are shorter in length and thus more rigid. Therefore short feeders are analyzed twice for fixed and free end conditions.

The number of feeders using different types of analysis, Type A or Type B, is showed in **Figure 7**. The ratio of total number of Type A vs. Type B is 5:1. For the most critical condition – after the PA switch when feeder thicknesses are at the lowest, Type A feeder, i.e. feeders with generic thickness profile requirement, is approximately 86% of total 480 feeders. For these feeders, pipe bend wall thickness can reach pressure based minimum thickness anywhere at bends while they only need to maintain a higher average thickness, which can be easily met from past feeder inspection experience. Only small number of feeders - 14% belongs to Type B analysis, in which specific thickness profile is required. For these feeders, specific thickness profiles are required for code compliance analyses, thus the interpretation or requirements for inspection data is more demanding, not only the lowest thickness but also its location, as well as sufficient data along the circumferential and axial directions should be available to define the bend thickness profile.

4.0 CONCLUSIONS

The generic thickness analysis methodology, i.e. Type A analysis, requires only information about the lowest and average thicknesses from the feeder inspection, thus it could significantly reduce inspection time, cost and more importantly, personal dosage. Type A requirements provide a greater flexibility to disposition local thinning problem during the outage. In Darlington feeder assessment, it is demonstrated that 86% feeders are in the category of type A. The rest of feeders require more information to define specific thickness profile to carry out further assessment.

5.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

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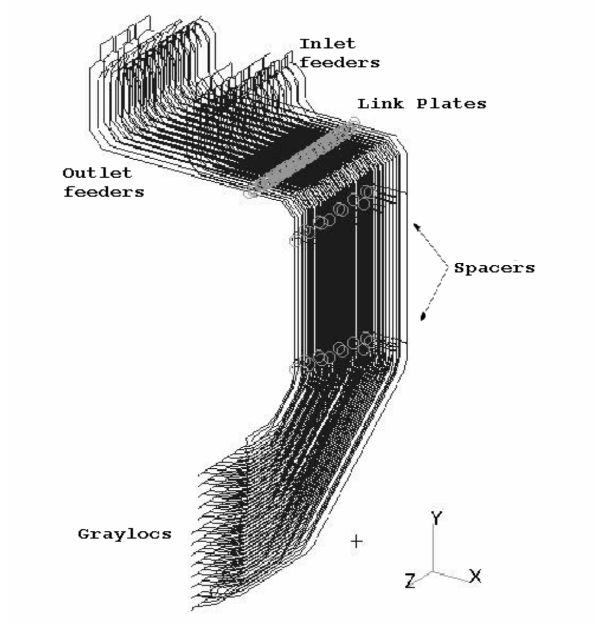


Figure 1 An Isometric View of a Linked CANDU Feeder Model

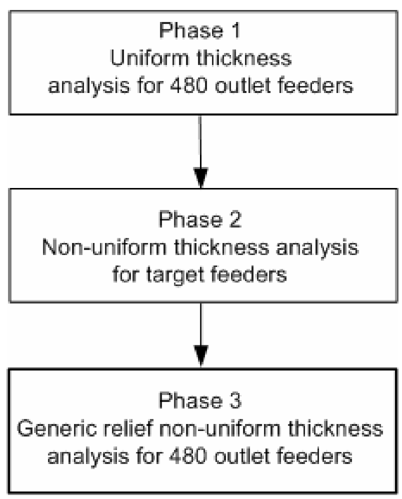
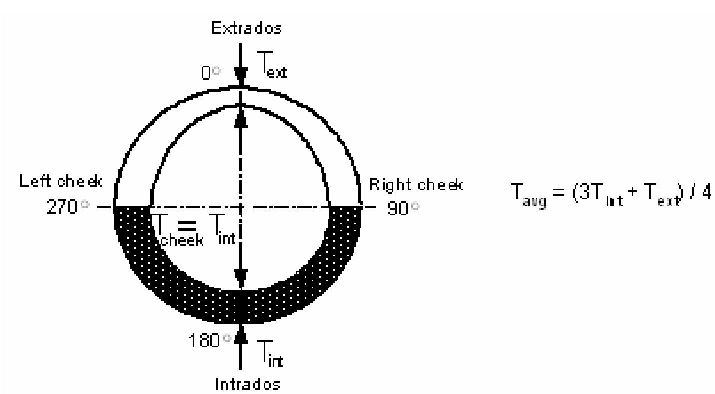


Figure 2 Overview of Darlington NGS Feeder Fitness for Service Stress Analysis



(where T_{ext} – extrados thickness, equal to minimum T_{min}; T_{cheek},T_{int} – cheek and intrados thickness)

Figure 3 Simplified Thickness Profile at a Degraded Pipe Bend

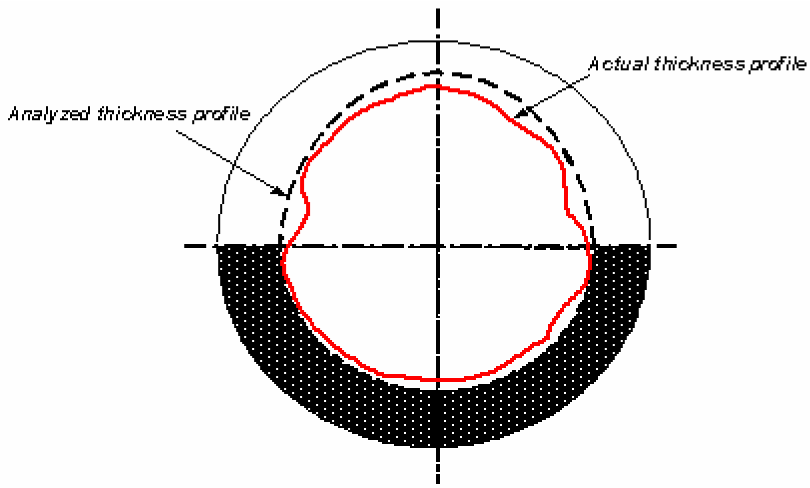


Figure 4 The measured or predicted thickness profile must be bounded by the Type B analyzed profile.

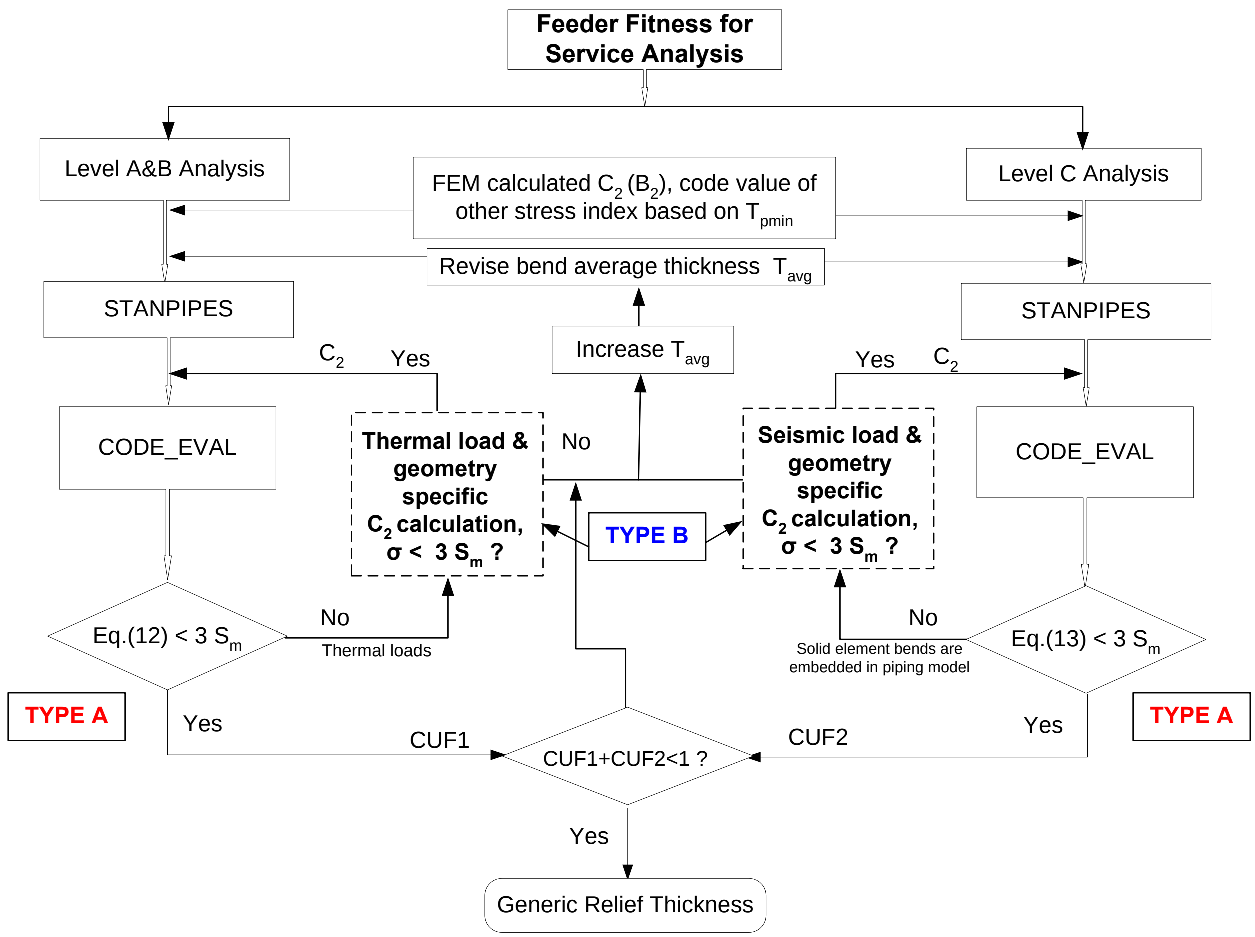


Figure 5 Type A and Type B Analysis Procedure Schematic

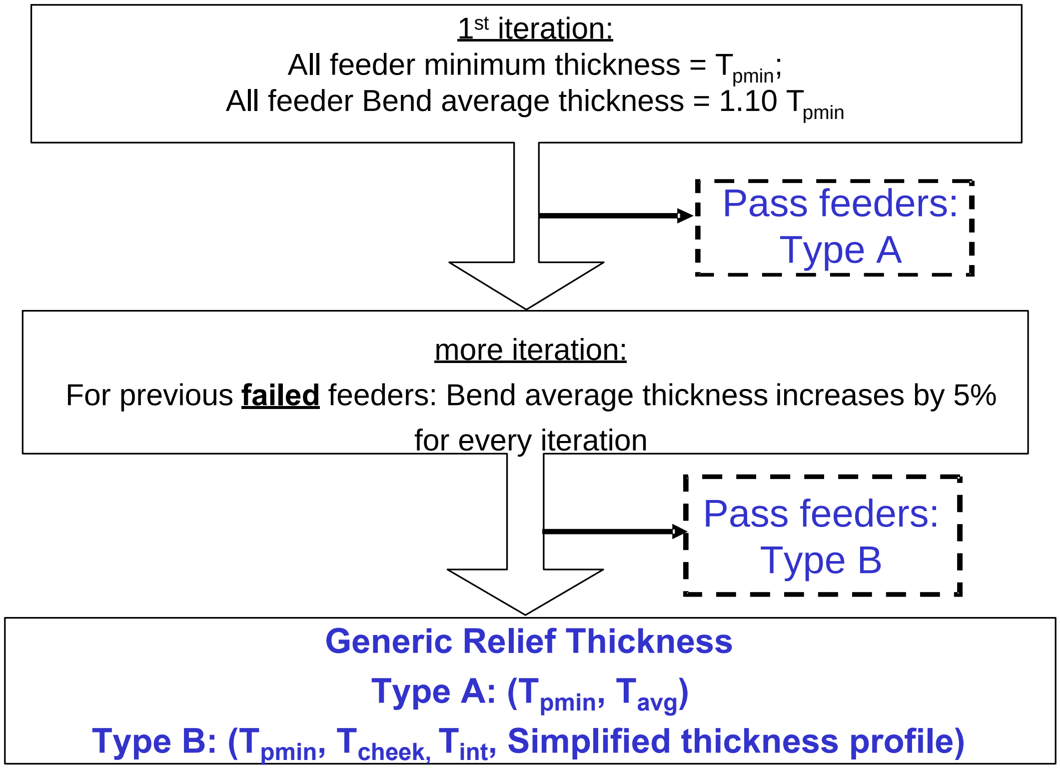


Figure 6 Analysis Iteration Schematic

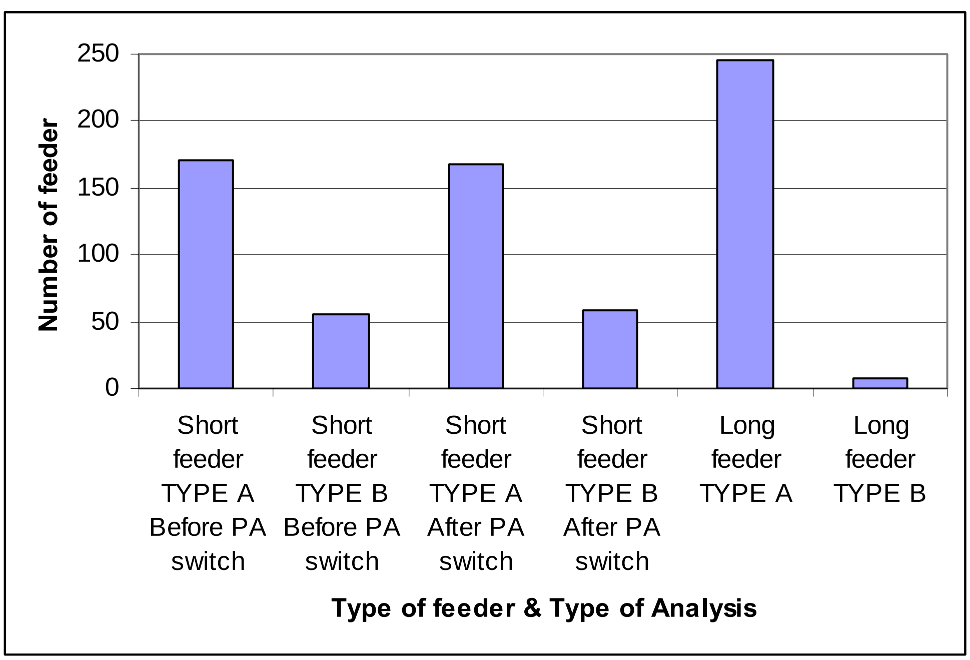


Figure 7 Number of Feeders Accepted by Type A or Type B Analysis