PROPOSAL OF AN ESTIMATION METHOD OF WELDING RESIDUAL STRESSES IN WELDED PIPES FOR RISK-ANALYSIS-BASED ASSURANCE OF STRUCTURAL INTEGRITY

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It is indispensable to evaluate welding residual stresses for assurance of structural integrity in welded structures. Since residual stresses have to be estimated nondestructively for operating plants, the bead flush method, which is based on the eigen-strain evaluation, has been proposed. In this method, welding residual stresses are calculated by an elastic analysis from eigen-strains that can be estimated by the inverse analysis from measured elastic strain changes when the reinforcement of the weld is removed. Although the accuracy of this method have been proved in welded plates and pipes with relatively high bead height, it is difficult to estimate reasonalby accurate residual stresses because absolute values of experimental errors usually become higher as the bead height decreases down to the actual level. Further problem is lack of statistical point of view for the risk assessment. In this study, to solve these difficulties, stabilizing methods are applied to the inverse analysis to restrict the space of solution and the released raw strain data are pretreated according to the foresight information.

1. Background

To assure structural integrity for operating welding structures, it is required to evaluate welding residual stresses, which play an important role on fatigue, fatigue crack growth and stress corrosion cracking. Today, as a nondestructive measurement method, the X-ray diffraction is commonly used and the ultrasonic method has been proposed as well [1]. However, the experimental results from these methods can not be applied to the FEM (Finite Element Method) which has been widely used in the assessment of structural integrity. Then, the eigen-strain method has been proposed [2]. In this method, welding residual stresses are determined from eigen-strains, which are defined as a sum of inelastic strains and can be regarded as the cause of residual stresses, elastic strains and welding deformations [3]. Using these factors, eigen-strain distributions can also be calculated by the inverse analysis [4]. As the eigen-strain can be applicable to the FEM analysis as initial strains such as thermal strains, three dimensional residual stresses in the whole structure can be calculated just by a simple elastic FEM analysis.

2. Methods

The objective of this study is obtaining reliable statistical distributions of residual stresses by using the BFM (Bead Flush Method) [5], which is a non-destructive evaluation method of welding residual stresses based on the eigen-strain evaluation. In this method, eigen-strain distributions are calculated by the inverse analysis from difference of elastic strains before and after removal of reinforcement of weld (Fig. 1). Here, a toe of weld may become a crack starter, so eliminating of excess weld metal is rather a preferable treatment. Therefore, this method can be regarded as non-destructive evaluation essentially and applicable to operating structures. So, the same FEM model that has been used to evaluate the structural integrity in the design process can be reused directly for this procedure in the in-service inspection. Actually, the effectiveness of this method has been proved for welded plates and pipes with relatively high bead height [6][7]. On the other hand, estimation accuracy for welded pipes with lower bead height is still poor because sufficient information can not be obtained during the inverse analysis [8]. Further problem is lack of statistical point of view for the risk-based-analysis. To solve these difficulties, following methods are proposed. Firstly, several lines of released raw strain data, whose values are almost the same when no experimental errors exist, were averaged before conducting the inverse analysis. In this experiment, measured released strains with similar values of any 7 lines (Total 8 lines) were averaged and thus total ${}_8C_7$ averaged data were acquired (Fig. 2). Since it is assumed that observation error follows the normal distribution whose average is 0 and the standard deviation is 20μ strain, reasonably reliable statistical data can be acquired by a simple series of removal without conducting multiple experiments. Secondly, to overcome the ill-posed problems in this inverse analysis, the TSVD (truncated singular value decomposition) [4] and the artificial noise method [4] were applied as stabilizing methods in the inverse analysis. Thirdly, these stabilizing methods were developed and the space of the solution was narrowed down in consideration of foresight information.

3. Results

Stabilized by applying the TSVD method, total ${}_8C_7$ estimated residual stress distributions in the axial direction in rank-2 and rank-3 as well as the exact distribution are shown in (a) and (b) of Fig. 3, respectively. Distributions of rank-2 have higher stability with poor accuracy. On the other hand, estimated results of rank-3 show unstable tendency on the surface although some of distributions have relatively sufficient accuracy. Then, we eliminated inaccurate results of rank-3 by considering output characteristics in the inverse analysis and more reliable stress range was acquired as depicted in (c) of Fig. 3. The maximum value of the rank is 12 that is consistent with unknown parameter number in this study, so the number of option for stabilizing degree is twelve. On the contrary, stabilized by the weighted artificial noise method, any level of stabilization can be chosen because real number instead of integer can be applied as the artificial noise. Therefore, it was possible to obtain estimated residual stresses with higher accuracy and stability as shown in Fig. 4.

4. Conclusions

The bead flush method, which makes it possible to calculate welding residual stresses nondestructively by a simple elastic FEM analysis, was developed applicable to welded pipes with relatively low bead height. The following findings were obtained. (1) Statistical range of residual stress distributions can be accumulated by changing the number of released strain data for averaging. (2) It is possible to narrow down the range of scatter band by using a property of effective ranks and its output characteristics in the singular value decomposition. (3) Reasonably accurate residual stress distributions can be evaluated stably by using the weighted artificial noise method.

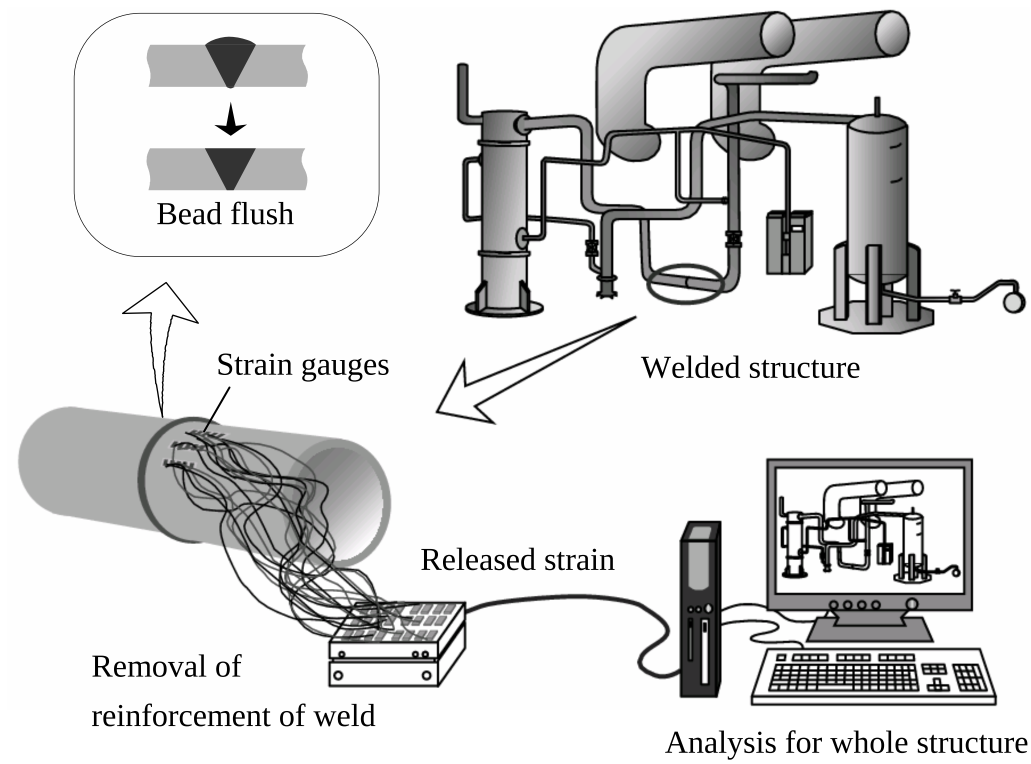
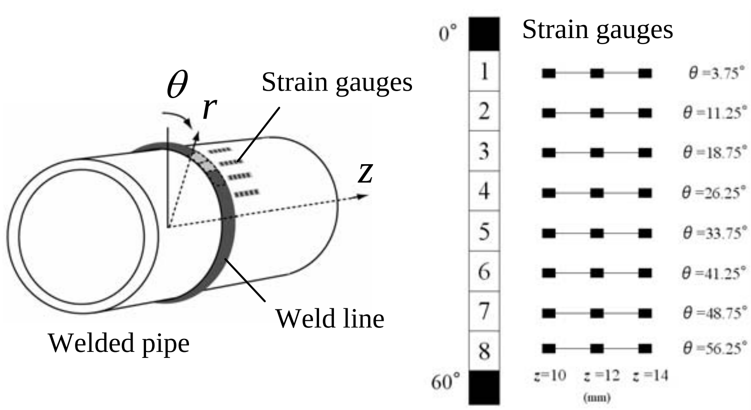
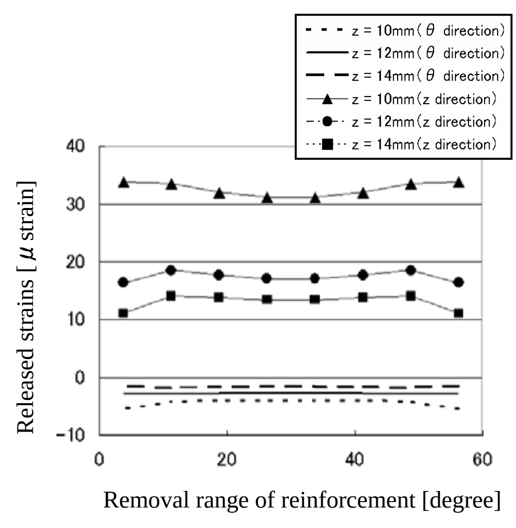


Figure 1: A concept of the bead flush method

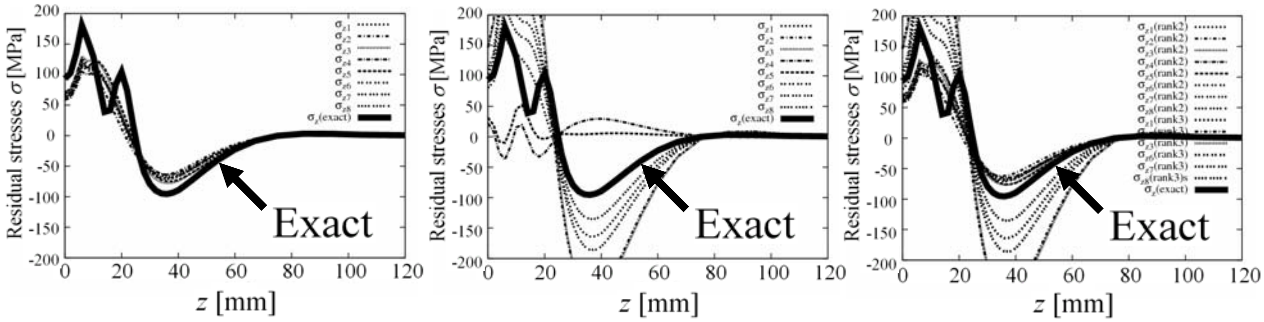


(a) Location of strain measurement



(b) Exact released strains

Figure 2: Measurement of released strains by strain gauges



(a) Optimized rank is 2 (b) Optimized rank is 3 (c) More reliable stress range (rank-2 and rank-3)

Figure 3: Estimated residual stress distributions in axial direction (stabilized by the TSVD method)

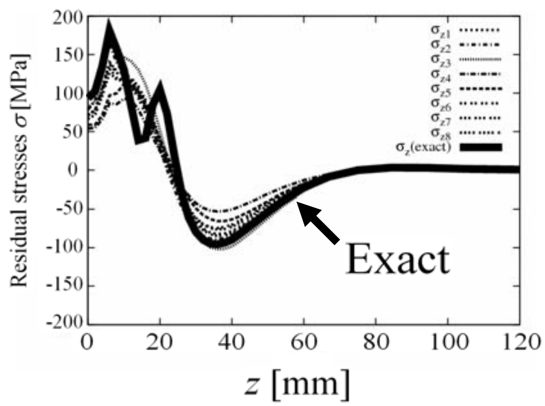


Figure 4: Estimated residual stress distributions in axial direction (stabilized by the weighted artificial noise method)

5. References

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