Correlation of Energy Balance Method to Dynamic Pipe Rupture Analysis

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ABSTRACT - When using an energy balance approach in the design of pipe rupture restraints for nuclear power plants, the NRC specifies in its Standard Review Plan 3.6.2 that the input energy to the system must be multiplied by a factor of 1.1 unless a lower value can be justified. Since the energy balance method is already quite conservative, an across-the-board use of 1.1 to amplify the energy input appears unnecessary. The paper's purpose is to show that this "correlation factor" could be substantially less than unity if certain design parameters are met.

In this paper, results of nonlinear dynamic analyses were compared to the results of the corresponding analyses based on the energy balance method which assumes constant blowdown forces and rigid plastic material properties. The appropriate correlation factors required to match the energy balance results with the dynamic analyses results were correlated to design parameters such as restraint location from the break, yield strength of the energy absorbing component, and the restraint gap. It is shown that the correlation factor is related to a single nondimensional design parameter and can be limited to a value below unity if appropriate design parameters are chosen.

It is also shown that the deformation of the restraints can be related to dimensionless system parameters. This, therefore, allows the maximum restraint deformation to be evaluated directly for design purposes.

1. INTRODUCTION Two methods commonly used for pipe rupture analysis are the dynamic computer analysis method and the energy balance method. The first method is elaborate and time consuming. It requires the use of a digital computer to perform the computations accounting for the multiple-degree inertia effects, plastic behavior, and nonlinear geometric effects. The second method uses a simplified model, such as a rigid-plastic model, and assumes the total energy exerted by the blowdown force is absorbed by plastic deformation of the restraint and deformation of the pipe at a plastic hinge.

The NRC's SRP 3.6.2 specifies that an amplification factor of 1.1 is to be used with the input energy, unless a lower factor can be justified. Since the energy balance method is already quite conservative, an across-the-board use of 1.1 to amplify the energy input appears unnecessary. It is the purpose of this paper to show that, for a given energy balance model, the "correlation factor," K, can be related to a nondimensional quantity constructed from the restraint design parameters, such as blowdown force, restraint location, restraint gap, and yield strength of the energy-absorbing component of a restraint.

Two types of energy-absorbing components of pipe rupture restraints are considered in this investigation. One is the ductile bolts of an omnidirectional restraint and the other is the laminated strap restraint, both made from highly ductile Type 304 stainless steel.

Two energy balance models are considered, both based on rigid-plastic material properties. In both models it is assumed that a dynamic plastic hinge will develop instantaneously and the pipe will rotate about the hinge as a rigid body. In one model the plastic hinge is included in the energy absorption; in the other it is ignored. The input energy multiplied by the correlation factor, K, is then equated to the energy absorbed by the pipe rupture restraint and, if applicable, the bending of the pipe at the plastic hinge. Through this relation, the correlation factor, K, can be expressed in terms of the maximum deformation of the restraint, d, and other restraint design parameters. By substituting the maximum restraint deformation, d, obtained from a dynamic analysis into this expression, the correlation between these energy models and the dynamic analysis can be established.

The results from dynamic analysis of a number of pipe rupture restraints actually designed for two nuclear projects were included in this study. In addition, a typical pipe rupture case, contrived from a 20-inch Schedule 100 piping system in which the restraint design parameters were systematically varied, was also included. Plots of the results are shown and can be used for the review or design of restraints using these energy balance models. A plot of the maximum restraint deformations from the dynamic analyses versus another nondimensional parameter is also included.

2. ENERGY BALANCE MODELS Referring to Figure 1, the energy input to the system (E_i) is evaluated by multiplying the blowdown force (F_b) times the pipe displacement (D) at the end of the pipe and a factor K_I which will be used later in this paper to determine the relationship between the energy balance method and the dynamic analysis.

Thus:

$$E_i = K_I F_b D = K_I F_b (a+d) L_h / (L_h - L_x)$$

This model assumes that a dynamic plastic hinge developes instantaneously and the pipe will rotate about this hinge as a rigid body. The hinge location is given by Reference [1] as

$$L_h = (3Mp/2F_b)(1+[1+(8F_b L_a/[3Mp])]^{\frac{1}{2}}) \qquad (1)$$

where Mp is the plastic moment of the pipe, F_b is the blowdown force, and L_a is the length of pipe between the break and the elbow.

The energy absorbed (E_b) by the bending pipe and the deformation of the restraint is given by

$$E_b = Mp(a+d)/(L_h-L_x) + E_a$$

where E_a is the energy absorbed by the restraint, a is the restraint acceleration gap, and d is the maximum restraint deformation.

Setting $E_i = E_b$ we get:

$$K_I F_b (a+d) L_h/(L_h-L_x) = Mp(a+d)/(L_h-L_x) + E_a \qquad (2)$$

Equation (1) defines the location of the instantaneous plastic hinge when the length of the straight pipe is sufficient to allow it to develop. If a pipe anchor or a pipe elbow is located close to the pipe whip restraint such that L_t, where L_t is the length of the pipe from the break to the pipe anchor or the next pipe elbow, is smaller than L_h, the quantity L_h in the left-hand side of Equation (2) should be replaced by L_t since the pipe would rotate about the pipe anchor or the pipe elbow in this case. The L_h in the right-hand side of Equation (2) is kept unchanged for $L_t < L_h$ to conservatively reduce the energy distributed to the bending pipe. Therefore, Equation (2) becomes

$$K_I F_e (a+d) = Mp(a+d)/(L_h-L_x) + E_a \qquad (3)$$

where $F_e = F_b L/(L-L_x)$, and L is the smaller of L_h or L_t. Equation (3) is the energy relation for the Model I pipe/restraint system investigated in this paper. By ignoring the pipe bending effect in the above equation, we have the energy relation for the Model II pipe/restraint system as

$$K_{II} F_e (a+d) = E_a \qquad (4)$$

Using the blowdown force and restraint energy defined in the following two sections, the maximum deformation of the restraint (d) can be obtained from Equation (3) or (4) for given restraint parameters and a given factor K (K_I or K_{II}). However, this paper is intended to determine the K factors such that these energy balance models can match the results from the dynamic analysis. This is done by substituting the maximum restraint deformation from the dynamic analysis into these equations and solving for the factor K.

The above models assume the pipe rotates about a hinge point, located at either L_t or L_h. For cases where the acceleration gap is less than 1 inch this hinge assumption no longer holds true and the models do not adequately describe the system. For this reason, therefore, gaps of less than 1 inch are excluded from this study.

3. EVALUATION OF CONSTANT BLOWDOWN FORCE (F_b) FROM FORCING FUNCTION In using an energy balance approach, a constant blowdown force (F_b) is assumed to act throughout the pipe rupture event. In general, however, the force acting through the event is not constant and is approximated by a stepped forcing function (see Figure 2). The force to be used in the energy balance method is the greater of F_2 or F_3 for the given forcing function. The initial blowdown, F_1, is ignored in the evaluation since its duration is short (less than 5 milliseconds for a great number of rupture cases), and its contribution to the total energy input is insignificant.

4. RESTRAINT TYPES UTILIZED Two restraint designs are used, an omnidirectional restraint and a laminated strap restraint, for this paper. Referring to Figure 3, the omni restraint completely surrounds the pipe and is utilized when loading could occur in any direction lateral to the pipe. The restraint employs ductile stainless steel bolts and compressive honeycomb panels as energy absorbers; the bolts take the force components acting in the P_1 direction, and the honeycomb takes the force components acting in the P_4 direction. In this paper we will only be concerned with loading cases where the force is acting only in the P_1 direction; i.e., the load is taken entirely by the bolts. The second restraint type, the laminated strap restraint, is shown in Figure 4. This restraint uses a number of ductile stainless steel straps, combined into the "U" shape shown in the figure, to absorb the load. This restraint is utilized when the loading is only in the P_1 direction. For a more detailed description of these restraints see Reference [2].

5. ENERGY ABSORPTION EXPRESSIONS FOR RESTRAINTS Both ductile bolt and laminated strap cases utilize a bilinear force-deflection (stress-strain) relation. This was done as the computer program, against which the energy balance results are to be compared, utilized a bilinear material relationship. This energy relationship is given by:

$$E_a = \frac{1}{2}(K_2d^2+(K_1-K_2)d_y(2d-d_y)) \tag{5}$$

where (see Figure 5) K_1 = AE/s, $K_2 = AE_p/s$, $d_y = F_p/K_1$, E = elastic modulus of bolt or strap, E_p = plastic modulus of bolt or strap, s = effective length of bolt or strap, F_p = yield force of bolt or strap, A = total cross-sectional area of bolts or strap, d = maximum deformation of bolts or strap, F_d = force corresponding to d.

6. DYNAMIC ANALYSIS Dynamic analysis of restraints from two different sources are considered in this study. The first is a contrived model where certain parameters were systematically varied to determine their effect on the deformation (d) of the restraint. As a single bilinear energy absorption expression is used for both laminated strap and ductile bolt restraints, one dynamic model can be used to represent both cases. The piping system used for the model is a 20-inch diameter, Schedule 100 line. The parameters varied were the physical length of the pipe (L_t), the acceleration gap (a), the yield force of the restraint (F_p), and the location of the restraint from the break (L_x). A simplified forcing function was utilized for the model and assumes a constant blowdown force of 235 kips.

The second source of dynamic analysis is the inclusion of the results of several restraints actually designed for two nuclear projects. Among them, three are laminated straps and four are ductile bolts. The acceleration gap ranges from 1.45 inches to 4.26 inches, and the restraint yield force from 166 kips to 625 kips. The blowdown forces applied to the dynamic systems are stepped forcing functions as depicted in Figure 2.

In all cases, the dynamic analysis was performed using a nonlinear dynamic computer code called LIMITA2, Reference [3], a computer code capable of handling plastic behavior and gap element control in the analysis.

The maximum restraint deformation obtained from these dynamic analyses was substituted into Equations (3) and (4) to find the correlation factor K for the two energy balance models. The maximum restraint deformation, expressed as the nondimensional quantity $(d/a)^{\frac{1}{2}}$, was also plotted against another nondimensional quantity, constructed from restraint design parameters. Details are described in the following sections.

7. PARAMETER LIMITATIONS (1) The parameter Lr/L, where $L_r = L-L_x$, should be limited to the range $0.5 < L_r/L < 0.9$. L_r/L could not be much greater than 0.9 as, physically, this would place the restraint extremely close to, or even at, the elbow. Values of less than 0.5 could allow the pipe to rotate about the restraint, thereby defeating the purpose of the restraint in the first place. (2) The range of (F_b/F_p) for cases considered in this paper is $0.4 \leq F_b/F_p \leq 1.45$. (3) Acceleration gaps should be $1 \leq a \leq 4.5$ inch. (4) The range of K_2 for cases considered in this paper is $45 \leq K_2 \leq 125$ (kip/in.).

8. RELATIONSHIP BETWEEN K AND NONDIMENSIONALIZED PARAMETERS Using the results of the dynamic analysis, i.e., restraint deformation, K_I was plotted against the dimensionless parameter $(Lr/L)([F_p/F_b][d/a])^{\frac{1}{2}}$ yielding the plot shown in Figure 6. As can be seen from the upper bound curve, K_I increases linearly from 0.5 to 1.1 where it levels off at 1.1.

K_{II} was also plotted against $(Lr/L)([F_p/F_b][d/a])^{\frac{1}{2}}$ as shown in Figure 7. There is much less scatter in the data, with an upper bound that levels off at 0.85.

9. RELATIONSHIP BETWEEN RESTRAINT DEFORMATION AND NONDIMENSIONALIZED SYSTEM PARAMETERS
Results of the dynamic analysis show that the restraint deformation (d) is related to certain nondimensionalized design parameters. With deformation nondimensionalized as $(d/a)^{\frac{1}{2}}$ and using the parameter $X = (L_rF_b/LF_p)(L_r/a)^{\frac{1}{2}}$, $(d/a)^{\frac{1}{2}}$ is plotted as a function of X as shown in Figure 8. This plot also contains several cases of actual restraints designed using dynamic analysis, and as can be seen, these cases are in very good agreement with the rest of the data. An upper bound curve was fit to the data and is given by the expression $(d/a)^{\frac{1}{2}} = \frac{1}{2}(X)^{\frac{1}{2}}$. This curve may be used to estimate the maximum restraint deformation directly for given restraint design parameters. It may also be used in conjunction with the K curves for restraint design using an energy balance method, as described in the next section.

10. USE OF K CURVES AND $(d/a)^{\frac{1}{2}}$ CURVE FOR RESTRAINT DESIGN The K curves and the $(d/a)^{\frac{1}{2}}$ curve can be used to verify restraints already designed, using Models I or II. From the given design parameters the $(d/a)^{\frac{1}{2}}$ curve is used to first find d; the d value is then used in the K curve to evaluate K. If K is less than the value assumed in the original design, the design is satisfactory. If the evaluated K value is greater than the assumed value in the original design, the design should be reevaluated.

The combination of the K curves and the $(d/a)^{\frac{1}{2}}$ curve may also be used to determine the value of the correlation factor K required for a pipe rupture restraint design using energy balance Models I or II. As the K curve is an upper-bound curve, this design procedure would provide a larger margin of safety as compared with the procedure described in the previous section.

11. CONCLUSIONS
(A) As the K curves indicate (see Figures 6 and 7), a K value can be selected for an individual design case and thereby eliminate some of the conservatism inherent in the energy balance method.

(B) The correlation factor (K) can be related to dimensionless system parameters, within the parameter limitations stated earlier. Limiting values for K_I and K_{II} were found to be 1.1 and 0.85, respectively.

(C) The deformation (d) of ductile bolt and laminated strap restraints can be related to dimensionless system parameters within the parameter limitations stated earlier. This relationship may be used for restraint design purposes to evaluate maximum restraint deformation directly.

(D) The K curves may be used along with the $(d/a)^{\frac{1}{2}}$ curve to determine the K values for energy balance Models I or II, or to design a restraint or review a restraint being designed.

(E) Both K_I and K_{II} curves show the same trends and will yield compatible results. However, K_{II} is a much simpler expression and easier to use since it does not involve Mp.

REFERENCES

[1] Roemer, R. E., East, G. H., "Prediction of Large Deformation Pipe Whip and Barrier Impact: A Simplified Approach," ASME Publication No. 80-C2/PVP-48. August 1980.

[2] Spada, A. J., Goldstein, N. A., "Efficient Pipe Whip Restraint Design," ASME Publication 80-C2/PVP-54. August 1980.

[3] Stone & Webster Engineering Corporation ST-223, LIMITA2, "Nonlinear Dynamic Analysis of Plane Frames," 03/04, September 1980.

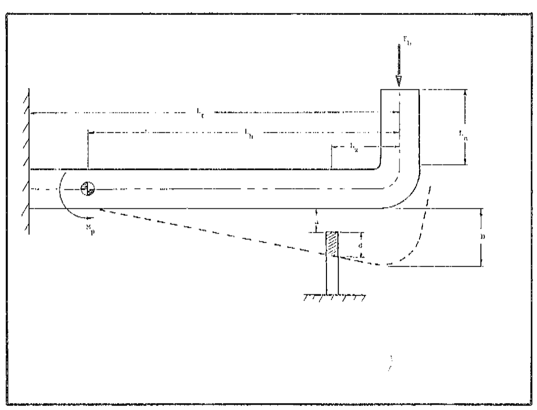

Figure 1 - Pipe-Restraint Model

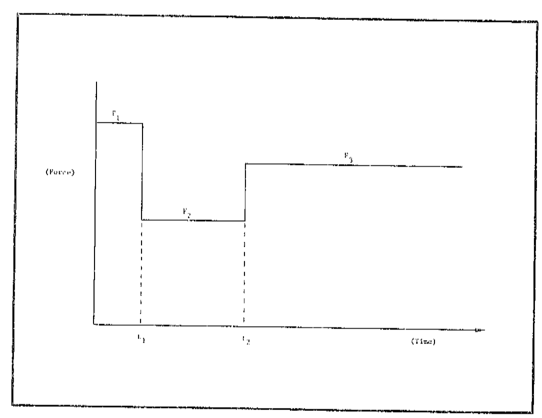

Figure 2 - Stepped Forcing Function

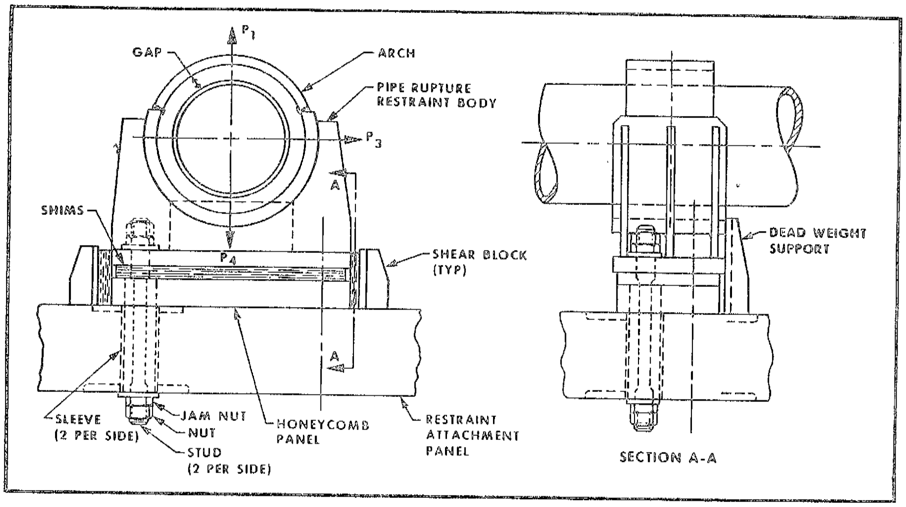

Figure 3 - Omni-directional Restraint

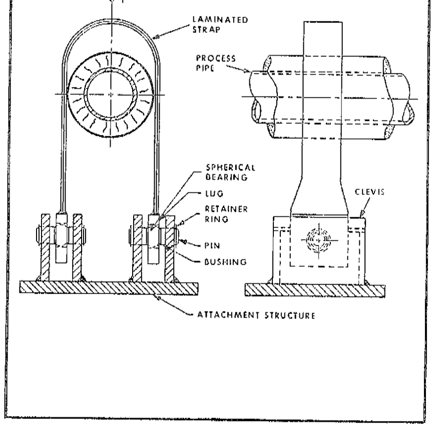

Figure 4 - Laminated Strap Restraint

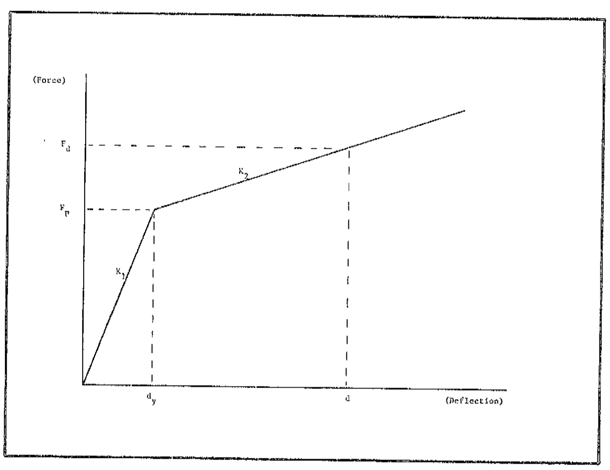

Figure 5 - Bilinear Force-Delection Relation

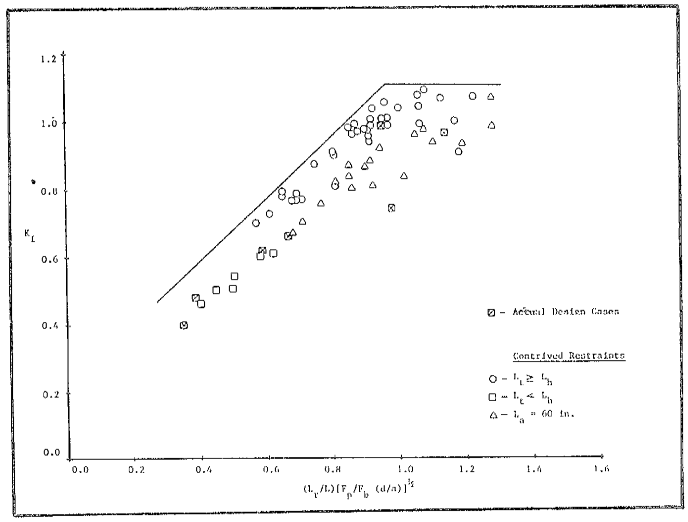

Figure 6 - K_I Curve

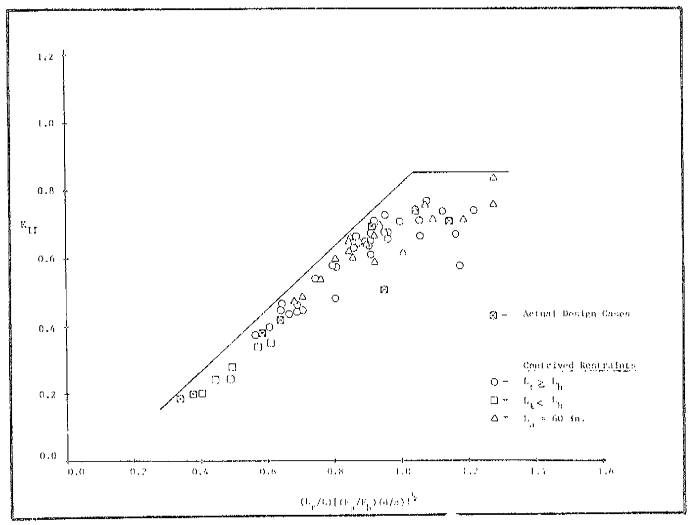

Figure 7 - K_{II} Curve

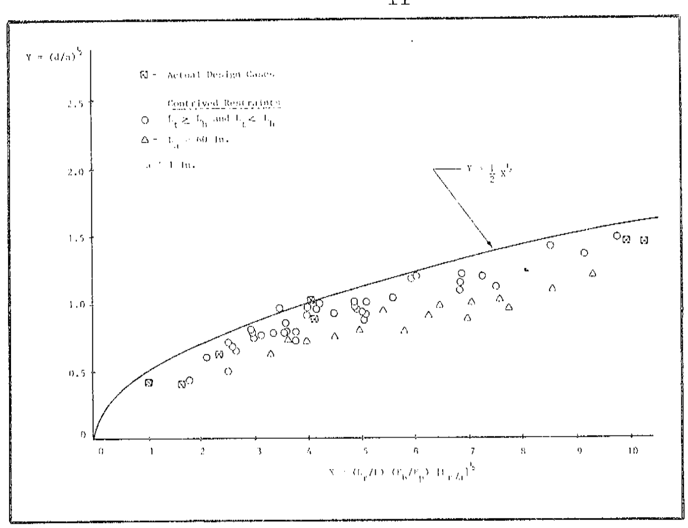

Figure 8 - $(d/a)^{\frac{1}{2}}$ Curve