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Effect of ductility on seismic response of piping systems

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ABSTRACT: This paper consists of two parts. The first part studies ductility capacity of six supports of an existing pipe run by calculating their static load-displacement relationships using the ANSYS computer program. The second part examines the effect of support and piping ductility on seismic response of (1) the above-mentioned existing pipe run and (2) an idealized piping model. The analyses were performed using ANSYS finite element step-by-step time domain integration procedure. Actual earthquake records were filtered and used as input to the piping systems. A total of 60 cases for the idealized model and 16 cases for the existing pipe run were studied.

1 INTRODUCTION

Nuclear power plant piping systems must resist both operational and earthquake loads. Due to overlapping conservatisms it is not uncommon that nuclear power plant piping systems employ a large number of supports resulting in overly rigid systems. It is commonly believed (Varadarajan et al. 1979; Mohammadi and Amin 1987; Lazzeri 1988) that if supports possess certain degree of inelasticity and that moderate amount of yielding is allowed in the system, loading on the supports will be reduced. As a result some of the supports may be removed, the system may be made more flexible and its safety enhanced. When reviewing piping systems to ensure operability for new or modified load cases, removal of conservatism inherent in the method of analysis may resolve many of the problems. For long term qualification and for sound design, it is of paramount importance to have an understanding of the inelastic behavior of components, piping supports and piping systems.

Nonlinear behavior of piping systems under earthquake loadings has been a topic of interest for the last twenty years or so. However, the emphasis has been on the development of appropriate methods for design/analysis purposes. There has been no report of detailed studies of load-displacement characteristics of existing supports in the open literature. Also, there is need for systematic study of the effects of system inelasticity on seismic response of piping systems.

The objectives of this study are to determine whether or not existing piping supports possess ductility and to ascertain that allowance of system inelasticity can be advantageous to seismic response. In this paper we report the results of an investigation of static analysis of six supports of an existing pipe run and the effects of ductility on seismic response of an idealized pipe run and an existing pipe run.

2 DUCTILITY OF EXISTING SUPPORTS

Six supports of an existing pipe run of early vintage, referred to as 'PS1' which will be described later in Sec. 3.1.2, were analyzed. The supports were modeled by finite elements using ANSYS. Nonlinearities due to plasticity, large deformations, gaps, uplifting of base plates, and expansion anchor deformation were all included. Many types of finite elements were employed either singly or in combinations to model the various parts of these supports in order to minimize the amount of computations required and to achieve maximum accuracy. A value of $36ksi$ was assumed for the support material yield stress and the modulus of elasticity was taken as $28,300ksi$. Load - displacement relationships were obtained for these supports under statically and monotonically applied forces. The results showed that 4 supports possess some ductility ranging from 1.5 to 2.7 but 2 supports failed in a brittle manner. The modes of failure of these supports take the forms of failure of expansion anchors, yielding of thin base plates, high strain concentration due to lack of adequate stiffeners or out of plane straining actions due to torsion. These supports are all very strong for the loads they were designed to resist and can be modified to possess ductility, if so desired, by appropriate detailing and anchorage improvement. A detailed account of the results can be found in another publication (Okeil et al. 1994). The benefit of having ductility is demonstrated next.

3 SEISMIC RESPONSE OF DUCTILE PIPING SYSTEMS

The task of studying the effect of pipe and support ductility on seismic response of piping systems is difficult and time consuming. Although existing pipe runs are the most representative of real life conditions, analyzing a large number of piping systems entails a great deal of computation time. Another approach is to study idealized piping systems. This can be carried out with relative ease covering a wide range of values of physical and geometric parameters involved. This study pursues both approaches by analyzing 60 cases of an idealized pipe run and 16 cases of PS1, modified by the removal of several supports to render the system more flexible.

3.1 *Description of piping systems*

3.1.1 *Four-span idealized system*

The first system studied is the idealized system shown in Fig. 1(a). It consists of a uniform beam (3-*inch* diameter pipe) supported at five supports of identical properties forming a 4-equal-span continuous beam (pipe run). To simulate continuity, the ends of the pipe run were considered to be attached to an imaginary span. Element type PIPE20 of the ANSYS element library was utilized to model the beam meshing each span into 11 elements. An idealized elasto-plastic stress-strain relationship was used to represent material properties of all the support components (and the piping). All supports were subjected to the same excitation. Because of the symmetrical nature of the problem, only half the system had to be analyzed.

The Melendy Ranch record of the Bear Valley Earthquake was filtered through a ten-story shear structure of uniform floor mass and column stiffness. The fundamental frequency of the structure was adjusted to 3 Hz by selecting the appropriate mass and stiffness values. A 4% damping ratio was assumed for each of the ten modes of the structure. The movement of the 10^{th} floor was used as the seismic loading imposed on the idealized pipe run. Figure 2(a) shows the acceleration time history of the top floor. The response spectrum generated from this record is plotted in Fig. 2(b).

For a combination of dead load, internal pressure and seismic load, the dynamic elastic and inelastic responses of the idealized pipe run were computed by ANSYS for an assumed Rayleigh damping ratio of 1% using the step-by-step time domain integration procedure with a time step of 0.002 seconds. Supports were considered as either completely rigid, linear elastic, or elasto-plastic. The elastic spring constant was assumed to be given by $K_{sup} = 2000EI/L^3$ where EI and L are respectively the rigidity and span length of the pipe. The span length, L, was given four different values (12, 18, 24, and 30 feet.) The excitation record was scaled to study the effect of pipe ductility on the response. Three excitation levels were considered. By changing the support yield level, P_{ult} (see Fig. 1(b)), the effect of support ductility may be examined. Three values of P_{ult} were considered. Thus, by considering 4 span lengths and 3 excitation levels, the number of cases analyzed is 12 for each of the cases of rigid and linear supports and 36 for the cases of elasto-plastic supports since in these cases three yield levels were considered. Altogether, a total of sixty different cases were studied.

3.1.2 *Pipe run 'PS1'*

Figure 3 is a schematic sketch of PS1. It runs from the regenerative heat exchanger to the containment wall where it is anchored. The nominal diameter of PS1 is $3 inches$ with an outside diameter of $3.5 inches$. PS1 is supported on six supports between its two anchors. These supports are the ones analyzed in Sec. 2. This system is considered a rigid one for it has fundamental natural frequency of 26 Hz. The materials of the supports and the pipe are all idealized as elasto-plastic and the yield stress and modulus of elasticity are taken to be the same as those of the idealized system.

Similar to the idealized system, PS1 was analyzed for a combination of dead load, internal pressure, and seismic load. The seismic load imposed was again filtered through a structure with a preset frequency. The ground motion was taken to be that of the El Centro record for the Imperial Valley Earthquake (May 18, 1940). All three components were used for the 3-dimensional analysis. Since PS1 is overly constrained, for the purpose of this study several supports were removed. Two modified configurations with fundamental natural frequencies of 4.6 and 9.1 Hz were selected. Supports were modeled first as linear elastic and then 3 yield levels were introduced to study the effect of inelasticity of supports. Excitation records were scaled allowing the pipe to yield. A total of 16 cases were analyzed.

3.2 *Results*

Idealized system analyses yielded in results that can be summarized in the following:

- Support ductility contributes to reducing strain experienced by the pipe if the support ductility demand is kept withing a reasonable range.
- Pipe displacements are generally not significantly affected by ductility. In some cases, pipe displacements are reduced especially for moderate values of support ductility demand.
- If some ductility is allowed in the system, supports can be designed for lower loads. The amount of reduction in support reactions can be substantial and depends on system frequencies, and available ductility in the pipe and the supports.
- Although the supports (as well as the pipe) undergo many cycles of loading throughout the duration of seismic excitation, excursion beyond yielding is rather rare.

Results obtained from the analyses involving PS1 follow the same trend of the idealized case. In all cases analyzed the maximum strain in the pipe was reduced. The maximum inelastic pipe displacements are only slightly different than those obtained from corresponding elastic analyses.

4 REDUCTION FACTOR FOR SUPPORT DESIGN

A primary goal of this research is to establish a design formula that can be conveniently used in verifying existing supports for operability purposes and also in designing future supports against seismic loads. The formula adopted follows that proposed by Hwang and Jaw (Hwang and Jaw 1989) for the design of concrete structure against seismic loads. The formula takes the form

$$(1) \qquad R_{elasto-plastic} = \frac{R_{linear}}{reduction factor}$$

where R_{linear} is the force (reaction) obtained from a linear elastic analysis and $R_{elasto-plastic}$ is the force (reaction) that the structure (support) should be designed for if ductility is allowed. The load reduction factor, R_{μ}, which is necessarily larger than unity, is determined based on the results of elastic and inelastic seismic response analyses of many structures (piping systems). From a total of 76 cases analyzed for the idealized pipe run and PS1, the relationship between maximum support ductility demand, μ_m, and the reduction factor, R_{μ}, are obtained and plotted in Fig. 4. This diagram shows that lower bound values for the reduction factor can be delineated. For example, by dividing the ductility demand into 3 regions, a constant value of reduction factor can be given for each region of ductility demand. Thus, for $\mu_m < 2.0, R_{\mu} = 1.0$, for $2.0 \leq \mu_m < 6.0, R_{\mu} = 1.1$, and for $\mu_m \geq 6.0, R_{\mu} = 1.2$. As more cases of existing and idealized piping systems are analyzed, the number of data points can be increased. Advanced "statistical analysis" method may be employed to yield more definitive values of reduction factor than the ones presently obtained based on using the minimum of the calculated values.

5 CONCLUDING REMARKS

To the best of our knowledge, this study presents the first attempt to systematically examine, in detail, the inelastic behavior, ultimate strength and ductility capacity of supports of existing piping systems, and to determine whether or not and to what extent system ductility serves to "reduce" seismic responses.

Based on the detailed analysis of the limited number of supports of existing pipe runs of early design, it may be said that the supports are very strong, but possess little, if any, usable ductility, but the ductility capacity of these supports can be improved. More analysis should be made for supports of more recent designs.

Our elastic and inelastic seismic response analyses of the idealized and existing piping systems indicate that system ductility acts to reduce seismic response of piping systems in the majority of cases studied. While similar analyses should be performed for more piping systems, it is safe to say that for operability review of nuclear power plant piping systems, system ductility can be used to advantage.

From our exploratory study, it appears that the idea of introducing the support load reduction factor is a viable one and should be pursued further by performing more seismic analyses of of idealized and existing piping systems.

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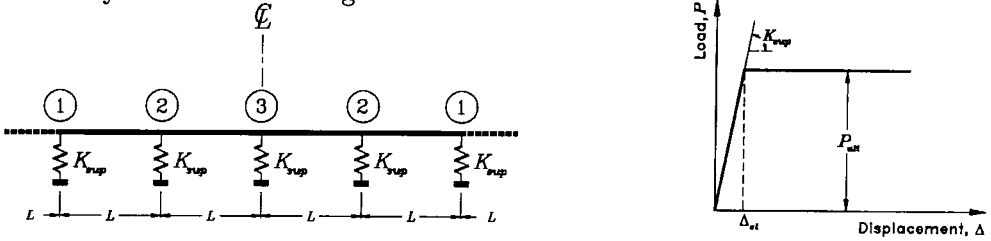
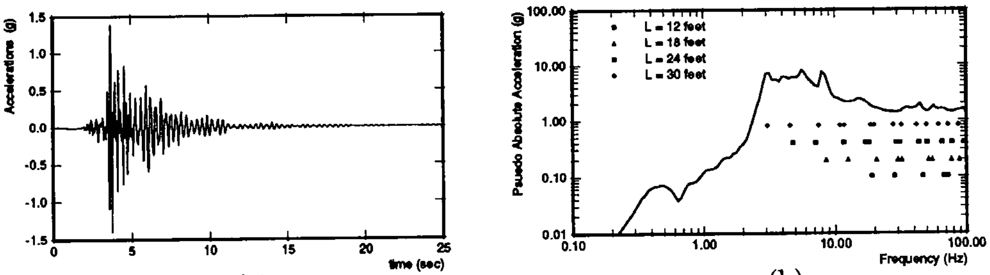


(a) (b)

Figure 1: Idealized System: (a)Four-span Pipe Run, (b)Support $P - \Delta$ curve



(a) (b)

Figure 2: Filtered Melendy Ranch Earthquake: (a)Acceleration Record of 10th Floor, (b)Response Spectrum and Natural Frequencies of Idealized Systems

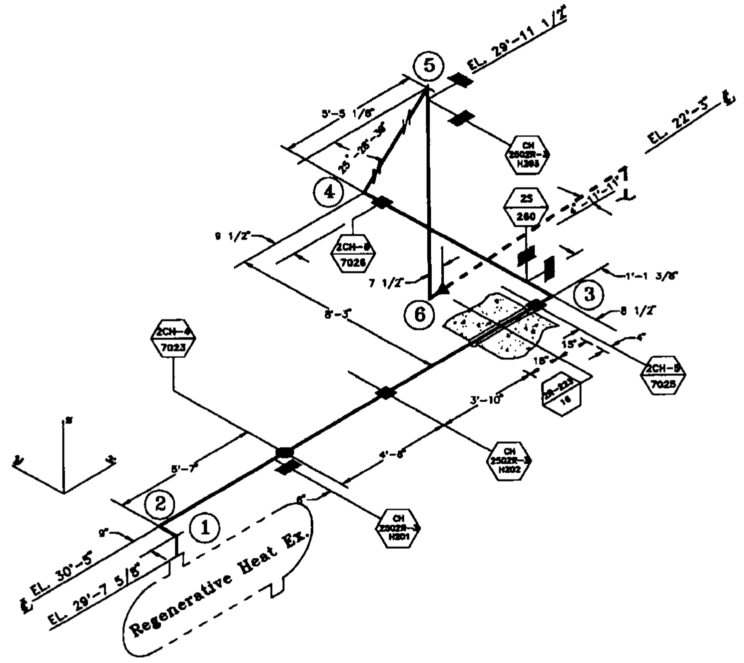


Figure 3: Schematic sketch of pipe run PS1

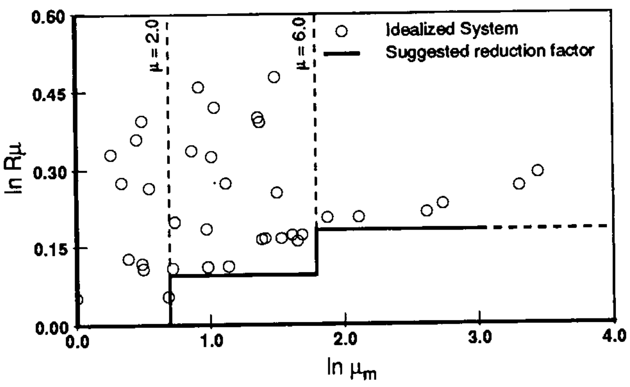


Figure 4: Lower Bound Values of Support Reduction Factor vs. Maximum Support Ductility Demand