Load Bearing Capacity of a Degraded Piping System Under Simulated Earthquake Loads and Operating Conditions

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INTRODUCTION

In the safe shutdown earthquake (SSE) loading scenario, which must be considered for nuclear power plants, permissible loads within systems are limited to stresses at levels equivalent to the ultimate stress of the respective material at the corresponding operating temperature (ASME Code, 1986 edition). This assumes that there are no defects in the systems. In this connection, it is of particular interest to discover and evaluate the behaviour, and the reserves in load-carrying capacity, of components with defects not to be discovered by NDE methods and thus postulated to be present (i.e., usually small defects).

TEST PROGRAM

Within the framework of Phase III of the HDR Safety Program (Katzenmeier et al., 1988) a weakened pipe system, Fig. 1 and 2, with predamaged components was subjected to repeated earthquake-like loads in two test series (Diem et al., 1988). The operating conditions chosen for these tests were these: $T = 240°C$, $p_i = 7$ MPa. The piping was loaded in two points by external vibrations generated by hydraulic cylinders. Each test took 15 seconds. The actual components tested were a weakened straight pipe section and a degraded elbow; both were integrated into the pipe system. However, the general object of investigation was the whole piping with its complex isometry and nominal bores between DN 100 and DN 300. The components subjected to prior damage were a 90° elbow made of highly ductile ferritic 15 MnNi 6 3 (external diameter, $D_o = 235$ mm; wall thickness $\bar{t} = 20$ mm, radius of curvature, $R = 305$ mm), and a straight pipe with dimensions in the area of the crack of $D_o = 114$ mm and $\bar{t} = 7$ mm. The weakened components were welded into the otherwise austenitic piping at two diametral positions.
The two components under examination had been subjected to cyclic fatigue stressing in the laboratory until a defined crack depth had been attained. The initial crack form in the straight pipe section at the beginning of the test series in the HDR was $2\alpha = 60°$

and $a/t = 0.4$. In the case of the elbow, a crack field developed during the cycling test along the bend flanks over practically the whole length of the elbow, with maximum crack depths of $a/t = 0.17$.

1st Test Series: Straight Pipe Section with Circumferential Crack

In the first test series, which was to cause the straight pipe section to fail under "earthquake" loads, a total of 108 single tests were carried out in three stages within an integral test. The first stage consisted of an earthquake-like vibration of the pipe system with levels of excitation of 100 %, 400 % and 600 %, repeated ten times in each case. The 100 % level of vibration in this case corresponded to the safe shutdown earthquake load level as defined for the HDR floor to which the piping used in the test was attached. In the second stage, the crack in the component under investigation was deepened by sineburst vibrations. The third stage again consisted of earthquake-like vibrations analagous to the first stage. The test sequence is shown in Fig. 3. At the 600 % vibration level, the resultant stresses always were above the maximum permissible levels for non-degraded components.
An on-line potential drop probe measurement with sensors applied to the outer surface of the pipe opposite the crack revealed a minimal increase in crack depth only during the 600 % vibration level in the first loading stage. Also in the intermediate stage when the crack was advanced to a new initial depth by means of sineburst vibrations in five steps each repeated ten times, small but continual crack growth could be observed. In the subsequent second "earthquake" loading stage, marked crack growth was detected already at the 400 % vibration level. At the 600 % vibration level, the gradient of crack growth changed drastically, as borne out by potential drop probe measurements, and the pipe failed by leakage in the 8th load repetition.
As a general conclusion, it can be stated that defects the size of those existing at the beginning of each of the "earthquake" loading phase, Fig. 4, did not cause failure even in the case of loads above the permissible level for non-degraded components. No failure occurred until the 8th repetition of a 600 % SSE in the second "earthquake-series".
After completion of the tests the damaged pipe section was removed from the piping and examined metallographically and fractographically. The cracking angle of $2\alpha = 60°$ on the inner surface had not increased. The through-crack length was $2\alpha = 8°$.

2nd Test Series: Elbow with Longitudinal Cracks

The second test series was to bring about failure in an elbow subjected to prior damage in the form of longitudinal defects by means of "earthquake" loading. This series of tests were carried out analogous to the first series, but with some differences in the intermediate stage generating a new initial crack depth for the second earthquake vibration phase. The test sequence is shown in Fig. 5. The intermediate result of the first "earthquake" load series was that neither the strain gauges applied to the outer surface of the elbow, nor the potential drop probe measurements revealed macroscopically detectable crack growth at any of the three vibration levels of 100 %, 400 % or 800 %.

In the subsequent test stage in which the initial cracks were to be increased to a new crack depth by means of sinebursts, various systems defects occurred, such as ruptured vent lines, failed brackets and leaking austenitic pipes with a nominal bore of DN 100, all of which caused numerous interruptions of the test.

In the second "earthquake" loading stage, the piping was first subjected to two cycles of a 100 % safe shutdown earthquake load level. Subsequently, the vibration level was increased by a factor of 4, and the piping was exposed to this new level twice. When, once more, no marked alterations of the cracks were registered, the piping was subjected to a third load level of 800 % SSE. After the second "earthquake" loading series of the elbow had ended without the component failing and without any crack growth being measured externally, a leakage occurred in a bimetallic weld of DN 200 during the first subsequent set of sinebursts which terminated the test series. At 800 % vibration levels, the resultant stresses were far in excess of the permissible limits for non-degraded components.

As a general conclusion, it can be stated that faults of a size such as those existing at the beginning of each "earthquake" loading phase, Fig. 6, did not lead to failure, even at loads in excess of the permissible ASME limits for non-degraded components. After conclusion of the tests, the weakened elbow was examined metallographically and fractographically. The inner surface of the elbow revealed typical multiple cracking in regions of concentrated loads as indicated by an ovalized cross-section on the elbow sidewalls, Fig. 7.

SECONDARY DAMAGE IN THE PIPING

As mentioned previously, secondary damage was encountered frequently in the second test series. Besides various failures of supports, a former primary steam header serving as a point of attachement became detached, thus immediately altering the vibration behaviour and reducing the loads on the elbow being tested. There were several ruptures in vent lines with a nominal bore of DN 25. Among the three leakages which occurred in the DN 100 austenitic bypass system, Fig. 8, there were two instances of circumferential cracks in welds connecting an elbow and a straight pipe section and an elbow and a reducer, and one instance of a longitudinal crack in a weld of a monocoque elbow. It should be noted that all these components had already been loaded in a previous earthquake test series (50 tests) at excitation levels between 100% and 800% SSE as well as in several sineburst tests (Flade et al, 1988). The fourth leakage, which occurred at a bimetallic weld (nozzle/straight pipe connection), brought the test series to an end.

SUMMARY AND CONCLUSIONS

Earthquake-like loads under operating conditions of a pipe system incorporating predamaged components allowed reserves in load carrying capacity to be determined even under conditions of excessive and repeated loading. In an integral test when the two initial crack depths were a/t = 0.4 and a/t = 0.7, a straight pipe section with a circumferential defect on at least seven occasions in each case withstood the loads exerted by a so-called 600 % "safe shutdown earthquake," in which the strain levels at the site of the defect attained a magnitude of 1 %, which is in excess of the permissible limit for integral piping systems. It was not until the eighth repetition of the 600 % SSE that failure by leakage occurred. In an analogous test program involving an elbow weakened by a number of longitudinal cracks, the initial crack depths of a/t = 0.17 and a/t = 0.4 were subjected to ten cycles in the first case and to one cycle of a 800 % SSE in the second case. During a transient condition of this type, which brought about strains in the region of $5\ 10^{-3}$ m/m to $10\ 10^{-3}$ m/m, there was no failure of the component.

REFERENCES

ASME Boiler and Pressure Vessel Code. Section III: Nuclear Power Plant Components, 1986 edition

Diem, H., Malcher, L.: Rohrleitungsversuche mit vorgeschädigten Komponenten unter überhöhter, erdbebenähnlicher Belastung und Betriebsbedingungen, 12. Statusbericht, HDR-Sicherheitprogramm, Karlsruhe, Dec. 1988

Flade, D., Steinhilber, H., Schrammel, D.: Verhalten eines Rohrsystems mit verschiedenen Abstützungskonzepten unter erdbebenähnlicher Belastung ("SHAM"), 12. Statusbericht, HDR-Sicherheitprogramm, Karlsruhe, Dec. 1988

Katzenmeier, G., Müller-Dietsche, W.: HDR Safety Program Phase III, PHDR Report No.05.42.88, Kernforschungszentrum Karlsruhe, October 1988

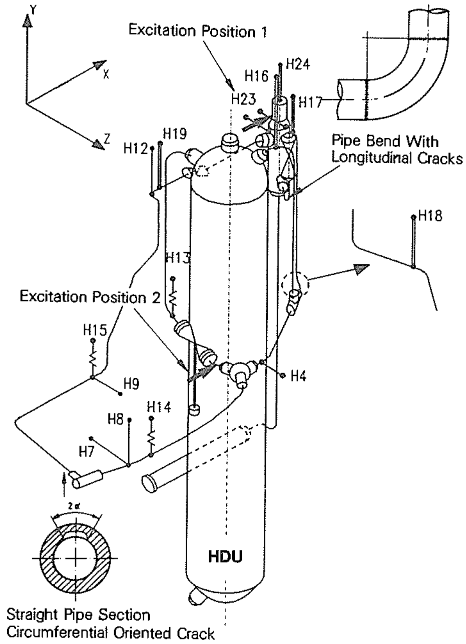

Fig. 1: System configuration of the 1st earthquake loading series

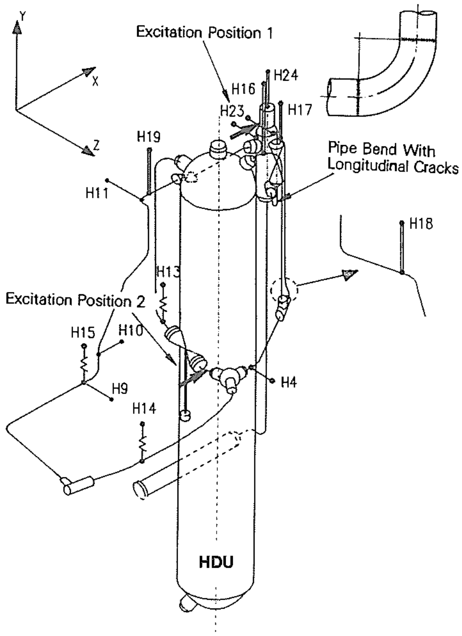

Fig. 2: System configuration of the 2nd earthquake loading series

Test Sequence, First Loading Series
Straight Pipe Section With Circumferential Oriented Crack

1. Earthquake Loading Phase	10 X 100% SSE
initial crack depth	10 x 400% SSE
a/t ~ 0.4	10 x 600% SSE
Fatigue Phase	Sineburst Loading
2. Earthquake Loading Phase	10 x 100% SSE
initial crack depth	10 x 400% SSE
a/t ~ 0.7	8 x 600% SSE
	leakage

Fig. 3: Loading history of the 1st earthquake loading series

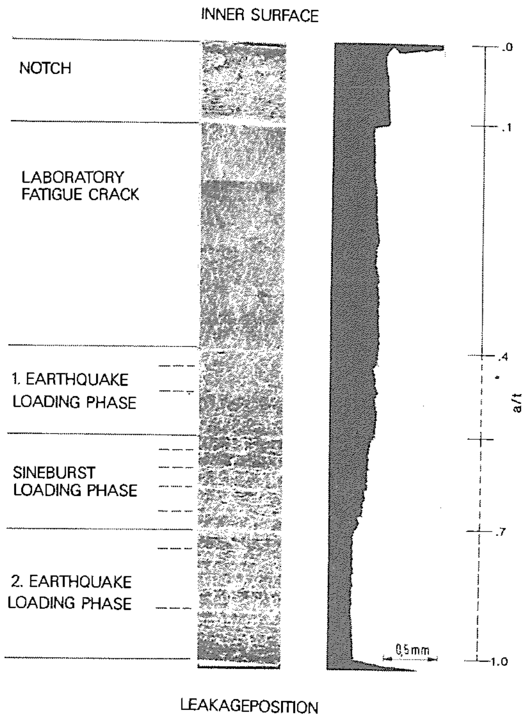

Fig. 4: Correlation between fracture surface and loading history (1st earthquake loading series)

Test Sequence, Second Loading Series
Pipe Bend With Longitudinal Oriented Crack

1. Earthquake Loading Phase	10 x 100% SSE
initial crack depth	10 x 400% SSE
a/t ~ 0.2	10 x 800% SSE
Fatigue Phase	Sineburst Loading
2. Earthquake Loading Phase	2 x 100% SSE
initial crack depth	2 x 400% SSE
a/t ~ 0.4	1 x 800% SSE
Fatigue Phase	1 x Sineburst
	Leakage at a bimetallic weld

Fig. 5: Loading history of the 2nd earthquake loading series

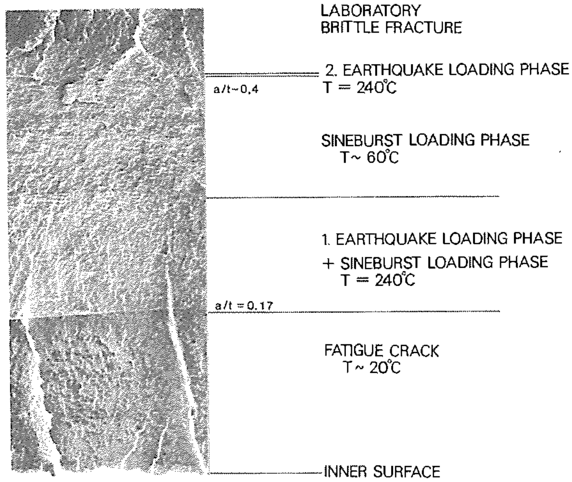

Fig. 6: Correlation between fracture surface and loading history (2nd earthquake loading series)

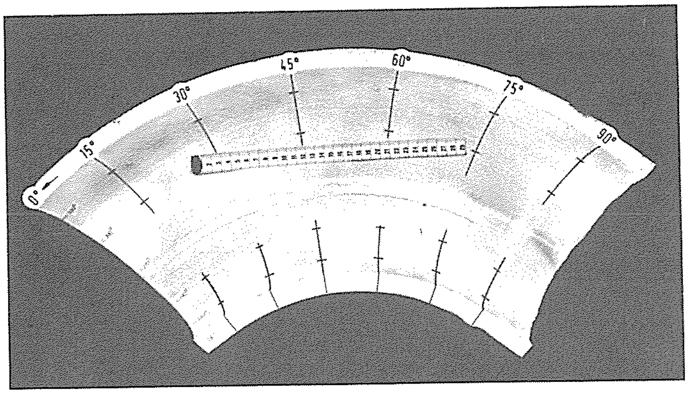

Fig. 7: Multiple crack field on the inner surface of the elbow flank

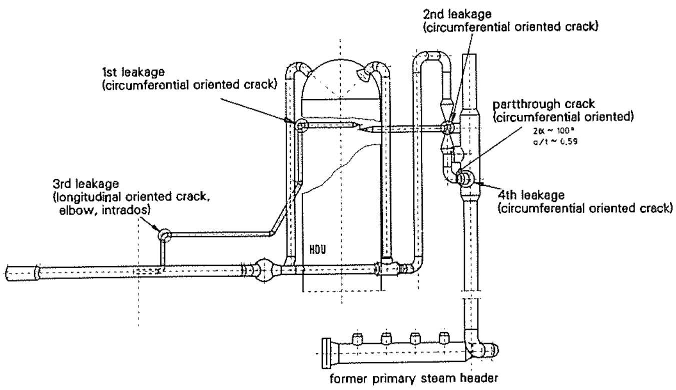

Fig. 8: Secondary damages within the piping system