EXPERIMENTAL STUDY ON THE EFFECT OF REPEATED VARIABLE LOADS ON STEEL PIPING COMPONENTS

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SUMMARY

The main problem which occurs in the calculation of the progressively increasing deflections, typical of incremental collapse phenomena of beams subjected to variable repeated loads, is the assumed material behaviour.

The incremental collapse problem is present in piping components, when, during emergency conditions, many overload cycles which exceed elastic limits are possible.

The scope of the present work is to find out how to consider material behaviour in the calculation; since the calculation should present as little difficulties as possible, while in the meantime it is necessary to obtain sufficiently accurate and technically meaningful results. In this paper piping components of plain carbon and of stainless steel, subjected to variable repeated loads, are considered.

Several specimens of a pipe fixed at its flanged ends, with two small radial branches, at 1/4 and 3/4 of its length, have been tested. A transversal load has been alternatively applied at the branches. Some tests have been performed using constant peak values of the cycling loads acting on the two sections. Others test have been performed with increasing levels of peak load on the same specimen. Permanent transversal displacement, as a function of the load cycles, have been evaluated, as they are the most meaningful results.

For the tests has been used a suitable load apparatus with an hydraulic system for automatic load sequences.

At first experimental results have been compared with those obtained by means of a simple computer program. This program is based on virtual displacement principle, elastic—perfectly plastic material behaviour, and plastic hinges concept. The calculated deflections have values larger than experimental ones. Moreover, the calculated shake-down load has always resulted non-significant from a practical point of view.

Strain hardening at least, among other factors that affect incremental collapse phenomena under variable repeated loads, must be considered, if significant values of plastic deformation evolution during cycles are to be determined. This is obviously still more true for stainless steel than for carbon steel. For this reason a computer program which considers strain hardening effects has been prepared. Without great difficulties, it has been possible to obtain some results in good agreement with experimental ones.

The following fundamental results have been obtained:

— the shake-down load obtained by means of limit analysis, is not significant in practical applications;
— for an effective determination of increasing deflections under variable repeated loads in plain carbon steel and stainless steel piping components, it is necessary to consider strain hardening effects, besides Young’s modulus and yield stress;
— a computer program, which considers strain hardening effects, has been prepared and its results compared with experimental ones; the program is relatively simple and theoretical and experimental results are sufficiently in accordance.

It has been started an experimental study of the behaviour of the model in alternating plasticity tests.
1. Introduction

The difficulties of predicting the behaviour of structures subjected to variable, repeated loads in the elastic-plastic range are well-known. They are connected with the choice of the material behaviour theory. On the other hand, plastic design is already permitted by some structural Codes. For example ASME III Code [1] accepts that under "emergency" and "faulted" operating conditions plastic analysis may be used for structural design.

Plastic collapse loads can be calculated by limit analysis, using the load-lower bound theorem. It can be checked that, under repeated loads, load does not exceed shakedown load. In both cases the material is assumed to behave in an elastic-perfectly plastic manner, strain hardening being neglected.

This paper is concerned with tests on plain-Carbon and stainless steel piping components, subjected to incremental collapse tests in order to compare actual structural behaviour with that predicted by the theory. Also some preliminary plastic collapse tests were performed on these components, as well as a few alternating plasticity tests, but these only on the Carbon steel specimens.

It is doubtful that the methods of structural calculus applied to elastic-perfectly plastic materials, under variable loads, as expounded by Neal and Symonds [2] and Massonnet [3] can predict the behaviour of the deflection as the number of cycles increases. Particularly for materials such as stainless steel, which exhibit to a marked degree strain hardening characteristics when the load in increased. This has been confirmed by the experiments described below.

Moreover (with alternating plasticity) it is very difficult to predict after how many cycles rupture will occur. In particular, it is hard to say if a load smaller than the shakedown one will guarantee that rupture will not occur during the first few cycles. We have tried to give a partial answer to the problems mentioned above.

Apart from experimental results, this paper also contains calculated results either assuming elastic-perfectly plastic behaviour or taking into account strain hardening. This part of the research is still in progress.

A number of our previous papers have dealt with the same topic [4, 5, 6]. Some tests described in [6, 7] have been repeated here with an improved experimental arrangement.

2. Specimens and experimental procedures

Each specimen consists of a straight pipe (length 1200 or 1326 mm, outer diameter 48.3 mm and thickness 3.2, 3.6, 3.68 mm) with a flange at either end and two small radial branches 1/4 and 3/4 of the way along the pipe (fig.1). The components are of three types: A and B are made of Fe 45 Carbon steel (an Italian standard Carbon steel with C = 0.22%) and C of AISI 304 stainless steel. The flanges and the welding of the flanges to the tube are in accordance with Italian standards. Table I shows the dimensional character-
istics and the standard and experimental ones for the material.

The model described above represents a possible simple component fixed at
the flanges and loaded radially at the two branches. The specimens have been
produced in accordance with standard procedures and have undergone standard
inspections.

The experimental arrangement used (fig. 2) it consists of a stiff beam
to which are attached two vertical supports for the bolted flanges of the
specimen. The beam is fixed at the base of a loading frame. On the two upper
cross-bars of the frame two hydraulic jacks are applied. They permit the
specimens to be loaded at the two branches. Between each jack and the corre-
sponding branch of the specimen there is an inductive load transducer, with
ball joints at its ends. In this way pure forces are transmitted, without mo-
ments.

Three inductive deflection transducer, one at each branch and one at the
center of the specimen, measure the deflection of the pipe. The moving pivot
of the transducer has a flat end and rests against a ring with spherical sur-
face. The rings are fixed to the pipe by pressure screws. In this way the
measured deflections correspond to those on the axis. In the diagrams it is
always the central deflection, considered the most significant reading, that
it is plotted.

The jacks are connected to a hydraulic system. The load cycles (or deflec-
tion cycles) are performed automatically by a specially designed programmer
that controls sequence of loads or deflections at both load points.

3. Experimental results

We thought it convenient to first determine experimentally the behaviour
of the models in Carbon and stainless steel in plastic collapse tests, with
the load gradually increasing up to collapse load. We define the experimental
collapse load $P_{ce}$ to be that load which causes a deflection, measured at the
center of the pipe, equal to twice the deflection produced by the same load,
assuming linear elastic structural behaviour. That is $P_{ce}$ is the load that
causes a residual deflection equal to an half of the total deflection under
the load.

Fig. 3 shows the collapse loads $P_{ce}$ obtained compared with the theoreti-
cal plastic collapse curve, with adimensional loads $f_1 = P_1/M_0$ measured
along the x axis and $f_2 = P_2/M_0$ along the y axis. The theoretical collapse
curve has been drawn, assuming plastic-perfectly plastic behaviour.

Fig. 4 shows the experimental load-deflection curves obtained for three
specimens made of Fe 45 (model A), with three load conditions (a single load
$P_1$; equal loads $P_1 = P_2$; unequal loads $P_2 = -0.61 P_1$) and one specimen in
AISI 304 with only one branch loaded. Fig. 4 also shows the theoretical values
of the deflection, evaluated using the method, developed by Weng [7], assum-
ing elastic-perfectly plastic behaviour. Table II summarizes the plastic col-
lapse load tests.
In Fig. 4 and Table II also are shown the experimental deflection $\delta_c$ corresponding to the theoretical plastic collapse load $P_{ct}$ and the deflection $\delta_c$ corresponding to the load $P_{ce}$ defined above.

Tests, consisting of the alternating application of loads at the two branches of the specimens were made. A cycle consists of first loading and then unloading the branches, one after the other. The load apparatus has been regulated at a frequency equal to one cycle per 20 sec.

For the Fe 45 model A have been performed four tests on as many specimens with alternating application on the branches of 1700, 2100, 2300, 2400 kp.

For AISI 304 model C has been performed at first a "step test", with successive application, each for 30 cycles, of the loads 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700 kp and successively four tests on four specimens with alternating application of 900, 1100, 1300, 1500 kp.

In figures 5 and 6 are shown, as the most significant results of this tests, residual deflection $\delta_c$ (determined at the end of the load cycles) as a function of the number of the cycles.

Moreover some alternating plasticity tests were performed on model B, made of Fe 45 steel.

In some tests an alternating load was applied to one of the two branches and in other tests an alternating deflection was applied. Five specimens have been tested with constant imposed peak load and ten with constant imposed peak deflection. Five of the latter specimens had undergone post weld treatment, in accordance with ANCC (Associazione Nazionale per il Controllo della Combustione) standards.

Fig. 8 shows the curves deflection-cycles and load-cycles. The deflection was recorded in the imposed-load tests and the load in the imposed-deflection tests.

Ruptures always appeared on the side of the load branch, at the base of the external weld between pipe and flange.

Fig. 9 shows the diagrams with the deflection (or the load) as a function of the number of cycles to rupture.

4. Analytical approach

The more sophisticated the theory describing the behaviour of the material, the more complex are the calculations.

By comparison with experimental results, we wanted to check the accuracy of the results predicted by certain of the theories.

For a sufficiently good approximation in the evaluation of the behaviour of the deflection under repeated variable loads, one must take into account the material strain hardening, as one can see from the comparison between experimental results and theoretical ones obtained on the hypothesis of elastic-perfectly plastic behaviour (figures 5 and 6).

As a first step a simple computer program was devised to simulate the variation of deflections and moments as a function of the number of cycles.
elapsed in a beam built in at the ends and subjected to an alternating load
applied at 1/4 or 3/4 of the way along its length. The computer program con-
siders plastic hinges linearly hardening when the applied moments exceed the
yield moment $M_y$. In this model the moment at hinge varies according to the
formula $M = M_y + K \phi$, were $\phi$ is the hinge rotation and $K$ the hinge hard-
ening coefficient.

A more sophisticated computer program is now being prepared. It evaluates
the deflections on the basis of the moment-curvature relation, taking into
account material strain hardening, without the hypothesis that the plastic
bending is concentrated at the hinge.

5. Remarks and conclusions

From the experimental diagrams of fig. 4 it can be seen that (at least
for the cases tested by us) the deflections due to an applied load equal to
Pct, are not much larger than that corresponding to a linearly elastic be-

haviour of the tube. Such a small value of the deflection is clearly due to
material strain hardening.

The experimental plastic collapse load $P_{cc}$ (as defined above) is 20% to
30% greater than the theoretical one (Table II). In fig. 3 the points repre-
senting the experimental collapse loads, for the Fe 45 model A, appear to
define a collapse curve roughly homothetic to, but larger than, the theoreti-
cal one.

From the incremental collapse tests one can see immediatly that the
theoretical shakedown load $P_{st}$ does not give rise to any noticeable discon-

tinuity in the pipe behaviour. In fact the residual deflection (measured after
shakedown has happened) changes smoothly enough with the load.

For a meaningful evaluation of deflection behaviour with load cycles it
is necessary to take into account strain hardening. Actually, even for low
loads, calculations that neglect strains hardening, give values for the re-
sidual deflections $\delta_r$ that are very much larger than those obtained experi-
mentally. Figures 5 and 6 show that the simple hypothesis of hardening hinges
will give acceptable results.

Figures 5 and 6 show some theoretical graphs of $\delta_r$ as a function of the
number of cycles for the same loads that were used in experiments. These
graphs were obtained using the strain hardening hinges model.

For the Fe 45 model A we introduced into the calculation a plastic mo-

ment $M_y$ corresponding to the yield stress $\sigma_y = 20$ kp/mm$^2$ (0.2% residual
stress) with $K = 15$ and $K = 25$.

For the AISI 304 model C, $M_y$ was calculated with $\sigma_y = 17$ kp/mm$^2$ (0.05% residual strain) and with $K = 30$ and $K = 40$. For the stress $\sigma_y$ some specimens
in AISI 304 gave rise, in standard tensile tests, to a considerable strain
hardening effect. From the calculus one can deduce that, with $K \neq 0$, after
a few cycles the pipe does shake down. From an experimental point of view,
phase with large deflections in first few cycles is followed, for larger
loads, by a progressive, slow increase in the size of the deflections.

The diagram in fig. 7 summarizes, for the Fe 45 and AISI 304 models the experimental and calculated incremental collapse results. The strip bounded by the two curves corresponding to $\delta_r$ deflections after 10 and 100 cycles is shown in the $P$-$\delta_r$ plane. Moreover, the analogous curves (related to $\delta_r$ obtained after shakedown has occurred) are drawn for $K = 0$ and for the two values of $K$ used for each model.

We note that it is possible, by taking into account hardening, using the strain hardening hinge model, to calculate conservative estimates which are however sufficiently near to experimental ones. Taking into account strain hardening in structural analysis permits one to make non-trivial economies, in particular where very expensive materials such as stainless steel are involved.

Making use of a rule similar to that used in defining the plastic collapse load $P_{ce}$, we define the conventional experimental shakedown load $P_{se}$ as the load which gives rise to a residual deflection $\delta_r$ (after a predetermined number of cycles) equal to twice the elastic deflection (with reference in the last case to a load applied at one of the two branches). For the models A and C (see fig. 7 and Table III) $P_{se} > P_{st}$.

The behaviour of the pipe under variable repeated loads can evidently be influenced by the duration of the loaded and unloaded states and by the load hold time. For this reason the tests have been performed with constant load cycles (identical cycles repeated every 20 sec).

The alternating plasticity tests have been made with a load significantly larger than the initial yield load. The latter coincides, in alternating plasticity, as is well-known, with the shakedown load.

Ruptures appeared after a very few cycles (fig. 9). For instance the load $P = 1400$ kp (that exceeds $P_{st}$ by only 27%), corresponding to an imposed deflection of $\pm 3.4$ mm, causes rupture after 800 cycles.

This part of the research is still in progress. We want to find the number of cycles to rupture for smaller loads than the ones applied above.
REFERENCES

[5] NERLI G., CITTI P., "Ricerca sperimentale sui carichi di collasso e sui fenomeni di assestamento plastico di una tubazione in acciaio", Proc. the Secondo Congresso Nazionale dell' Associazione Italiana di Meccanica Teorica e Applicata; Napoli (Oct. 16-19, 1974);
Table I - Specimens

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<tr>
<th>model</th>
<th>material</th>
<th>$\phi$ (mm)</th>
<th>$t$ (mm)</th>
<th>$l$ (mm)</th>
<th>$\sigma^+_0$ (kp/mm$^2$)</th>
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<td>F6.45</td>
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<td>56.0</td>
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<tr>
<td>B</td>
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<td>3.6</td>
<td>1326</td>
<td>39.2</td>
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(†) determined on pipes lot material

Table II - Experimental plastic collapse results

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<th>$P_{ct}$ (kp)</th>
<th>$P_{ce}$ (kp)</th>
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<th>$\delta^c$ (mm)</th>
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<tr>
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### Table III - Incremental collapse tests results

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<th>$d_r (30)$ (mm)</th>
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<th>$P_{st}$ (kp)</th>
<th>$P_{se}$ (kp)</th>
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<td></td>
<td>2300</td>
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<td></td>
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(*) calculated with $\sigma_0 = 20$ kp/mm² (0.2% residual strain)

(**) calculated with $\sigma_0 = 17$ kp/mm² (0.05% residual strain)

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**FIG. 1 - Specimen**
FIG. 2 - Experimental arrangement

FIG. 3 - Plastic collapse results
FIG. 4 - Plastic collapse tests results

FIG. 5 - "Step test" incremental collapse results
FIG. 6 - "Single load" incremental collapse results

FIG. 7 - Incremental collapse results resume
**FIG. 8** - Alternating plasticity tests results

**FIG. 9** - Alternating plasticity tests results