CHAPTER 118

Stresses in Tetrapods: Results of Large Scale Model Tests

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Abstract

This paper intends to review the experimental research work performed at the University of Hannover on the structural stability of tetrapods. It presents particularly the first results from the hydraulic and pendulum tests which suggest that:

- the most critical location of the armour units with respect to structural stability has been found at and slightly above still water level;
- for regular waves a well defined relationship can be found between incident wave parameters and the induced dynamic and quasi-static stresses. In the case of irregular waves, however a clear relationship appears to exist only for quasi-static loads;
- the critical IRIBARREN-Parameter with respect to structural stability is in the same range as the one found for hydraulic stability;
- a linear relationship has been found between impact bending stress and impact velocity for the tested tetrapods 50 kg - 1.8 t.

1. Introduction

It is now widely accepted that not only the hydraulic stability but also the structural integrity of concrete armour units should be considered in the design of rubble mound breakwaters. Due to a number of diffi-

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culties, no generally applicable criteria and procedures accounting for the breakage of the units and its effect on the whole armour stability are yet available. One of the difficulties is the determination of the actual load history for armour units in a breakwater environment.
The main objective of this paper is to contribute to a better understanding of the actual single impact loads and the subsequent impact stresses.

2. Description of the Research Program

The investigations on the structural behaviour of concrete armour units constitutes a part of an extensive basic research program on rubble mound breakwaters conducted at the University of Hannover and supported by the German Research Council (DFG) within the scope of the "Sonderforschungsbereich 205" (SFB 205). Aside from the research program on structural behaviour of concrete armour units, a number of aspects like hydraulic stability, internal and external flow field as well as geotechnical stability are also being investigated (BÜRGER et al., 1988). The different tests which has been performed on structural stability of the units are given in Fig. 1.

The main purpose of the hydraulic tests with respect to structural stability of the units was to determine the actual response of the units in a breakwater environment as a function of the incident waves and of the location of the units on the slope.

The static tests were primarily destinated to calibration as well as to verification purposes related to the sensitivity of the measuring techniques used.
The pendulum tests have been performed, aside from other objectives (BÜRGER et al.,1989), in order to:

a) compare the impact strain history of tetrapods with full cross section and of the same tetrapods with a reduced cross section,

b) develop a correlation between the recorded response of the units in the hydraulic model and that in the pendulum tests,

c) determine impact strain-time functions for instrumented model and prototype tetrapods.

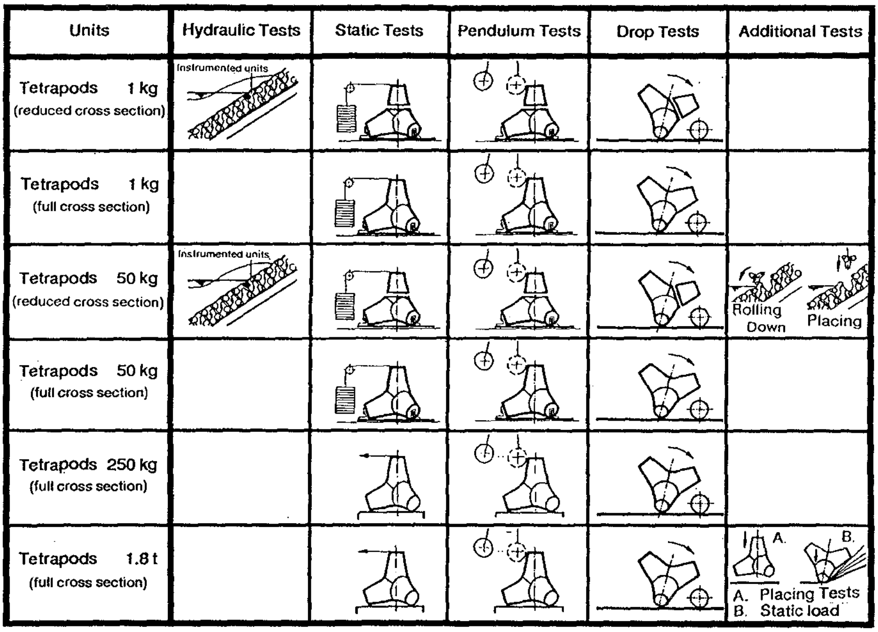


Fig. 1 Review of performed tests on structural stability at the University of Hannover

The results of the aforementioned experimental investigations, together with available results from basic research on impact and cyclic loading of concrete are intended to be used for the development of design criteria for the structural stability of the units.

Although a reliable design of concrete armour units with respect to their mechanical strength requires the consideration of all loads and environmental impacts (BÜRGER et al.,1989), the most relevant loads, however, are induced by the combined action of waves and the weight of the units.

3. Large Scale Hydraulic Model Tests

3.1 Description of the Breakwater Model and the Instrumented Units

Fig. 2 shows the cross section of the model in the Large Wave Channel, Hannover.

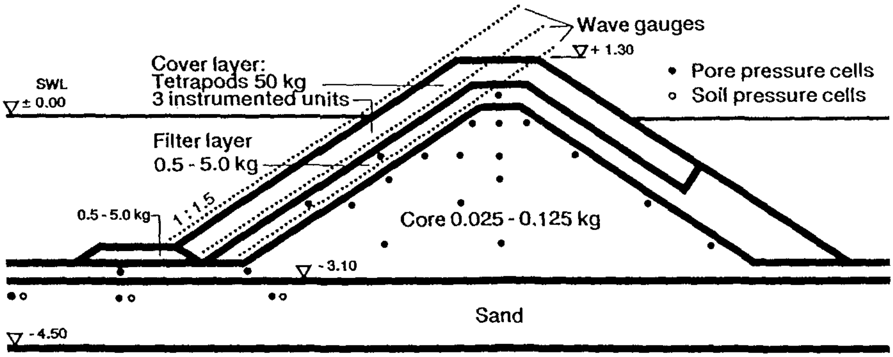


Fig. 2 Cross section in the Large Wave Channel (GWK)

The instrumented tetrapods used in the hydraulic tests had a reduced cross-section in order to measure the wave-induced static loads, quasi-static loads and to a certain extent also dynamic loads (Fig. 3).

Each of the oppositely applied strain gauges on the square steel bar was assigned to one recorder channel. Two signals are thus obtained on channels 1 and 2, respectively, when the tetrapod leg is subjected to load.

3.2 Calibration of the Instrumented 50 kg-Tetrapods

The sensitivity of the measuring instruments and the necessary amplification factor for the tests can be determined by calibration.

By increasing the load, the linearity of the measured values can be checked and both hysteresis and creep effects may be detected.

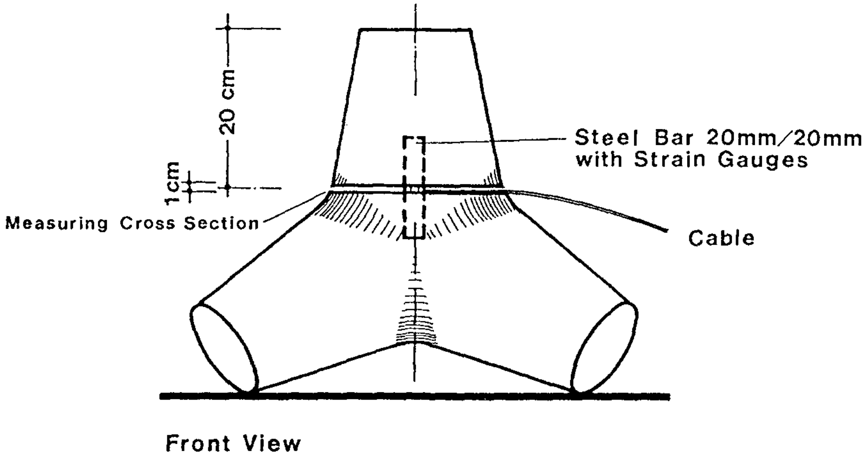


Fig. 3 50 kg-tetrapod with reduced cross section

On the test rig (Fig. 4) the tetrapod is centrally fixed and the load is transferred horizontally to the upwards directed leg by hanging on calibrated weights up to 100 kg in increments of 10 kg.

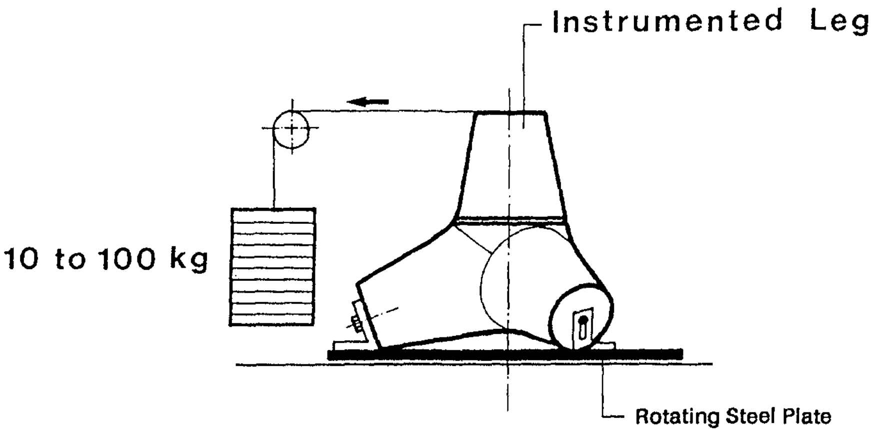


Fig. 4 Set-up for static tests

Strain and bending moments for both axes were recorded at each stage of loading. Thereafter, the leg was unloaded, the steel plate was rotated and the instrumented leg loaded once again.

To check the long-term behaviour of the strain gauge applications and also to determine whether a single calibration value was valid for all tests, a calibration was performed after each series of the hydraulic tests.

3.3 Testing and Recording Procedures for the Hydraulic Tests

3.3.1 Testing Procedure

Since the forces acting on a unit will show a large variability based on the units location and the wave climate, the tests covered up all critical locations on the breakwater (Fig. 5) and were performed with both regular and irregular waves, started with low wave conditions and increased in steps of 10 - 20 cm until a significant unit movement was observed.

After every test series, the cover layer was completely removed and reconstructed by the same persons, to ensure as far as possible similar positions of all tetrapods and similar porosity in all tests.

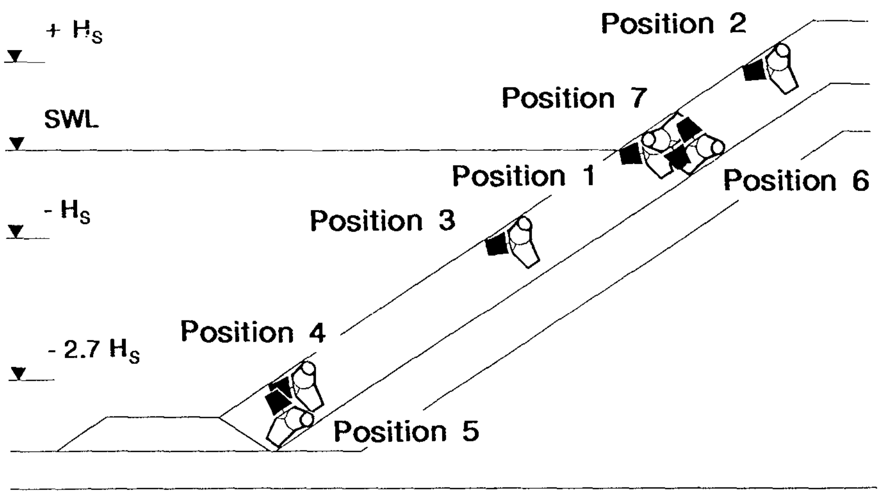


Fig. 5 Positions of the instrumented tetrapods

3.3.2 Data Collection and Recording Procedure

The measured data were recorded at a sampling frequency of 400 Hz. At the same time, the measured values were also registered at a sampling frequency of 11000 Hz by a Video Pulse Code Modulator (Video PCM).

All tests were recorded using two video cameras, one recording the whole armour layer, and the other one the instrumented units. So the movements, rocking or displacement, can be compared with the measured strain data.

Before and after every test, photographs were taken in order to determine the changes which occur in the whole armour layer and the instrumented units.

3.4 Data Reduction

Among the more recent results of hydraulic model tests using instrumented armour units only those of ANGLIN et. al. (1988) are related to the analysis of quasi- static load data. High frequency signals related to impact loading are not measured or are filtered out. However, only regular waves are used for the tests. Therefore, only an averaging procedure for the analysis of the results is adopted; i.e. the average load is determined for each test and then correlated to the wave parameters tested.

In contrast to this approach the tests performed in the Large Wave Channel at the University of Hannover are based on regular and irregular waves and consider all types of loads: static, pulsating and impact loads as well as slamming.
For the irregular wave tests, however, it is necessary to analyse the correlation between the single wave and the induced load. For the tests with more than one thousand waves the interaction between wave parameters and resulting load has to be described individually; i.e. separately for each wave.

The results of the static and dynamic calibration are two calibration factors, one for the static load, pulsating load and slamming (all together called quasi-static load), and the other for the dynamic load. Since the quasi-static and the dynamic load could not be measured separately, the recorded load signal should be splitted into a quasi-static and a dynamic part by a computer program developed for this purpose. This computer program provides a table containing the wave parameters and the resulting quasi-static and dynamic load for both channels of each tetrapod.

The steps of the program may be described as follows:

1. Identification of the wave occurrence and calculation of the wave duration by analysing the time series of the run-up gauge placed along the slope;

2. Determination of the wave height by analysing the time series of the wave gauge installed in front of the breakwater;

3. Step by step analysis of the measured strain-history for each instrumented tetrapod and both channels;

a) Adjustment to zero separately for every time window;

b) Calculation of the quasi-static strain by filtering the high-frequency signals;

c) Determination of the resulting maximum quasi-static strain according to the following formula:

$$\epsilon_{qs} = \sqrt{\epsilon_{qs1}^2 + \epsilon_{qs2}^2} \tag{1}$$

d) Evaluation of the dynamic strain by determining the difference between the zero-adjusted raw data and the quasi-static strain;

e) Determination of the maximum impact strain according to the following formula:

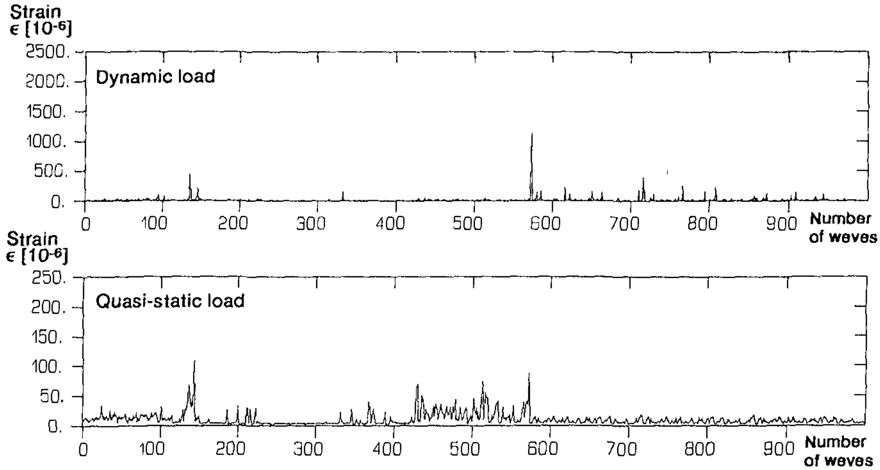
$$\epsilon_d = \sqrt{\epsilon_{d1}^2 + \epsilon_{d2}^2} \tag{2}$$

f) Print out of the values in a table for each test.

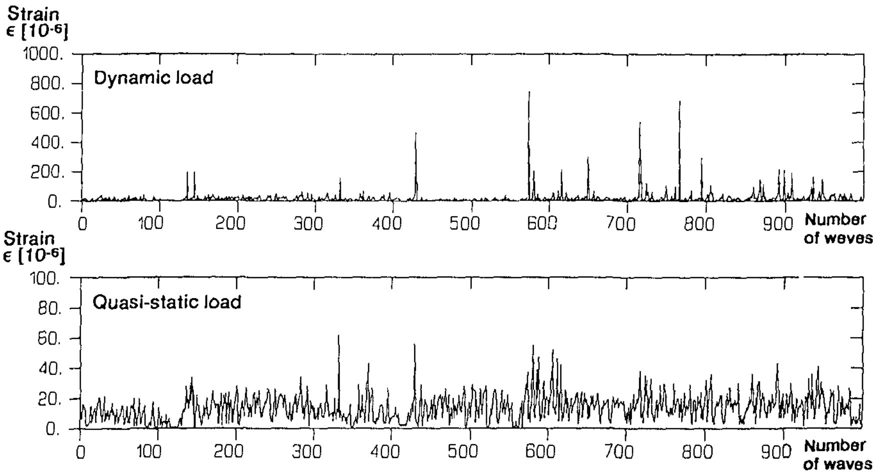
Fig. 6 a) and b) show the separated signals in the same test for both dynamic and quasi-static load and for two different positions of the instrumented tetrapods.

3.5 First Results

The position of each individual tetrapod is of a stochastic nature. When installing the instrumented tetrapods, it is not possible to position the instrumented legs in such a way that the pre-loading



a) Tetrapod D Position 1



b) Tetrapod F Position 7

Fig. 6 Strain records (Wave conditions: JONSWAP-Spectrum, H_S = 0.90 m, T_P = 4.5 s)

(static loading) is the same from one test series to the next. This also means that the point of contact between an instrumented tetrapod and its neighbouring one is not reproducible. Each reinstallation therefore represents a new loading variant.

Although the tetrapods occupy the same positions shown in Fig. 5 for various periods in the test series, the points of contact, and thus the strain or bending moments, are not directly comparable. As a rule, each test with new wave parameters and settlement during the running tests implies new bearing conditions.

Therefore, a first attempt to determine a relationship between strain and corresponding incident wave parameters resulted in a large scatter of the data, particularly for large wave heights (BÜRGER et al., 1989). Linear regression analysis led to correlation coefficients in the same range as found by ANGLIN et.al. (1988). However, a better correlation could be obtained by considering only the maximum strain-values (BÜRGER et al., 1989).

From the analysis of the data related to the location of the instrumented tetrapods, the highest wave-induced stresses within the tetrapods generally occur at and slightly above the still water level.

Some results from the tests with irregular waves are shown below.

Selected are the locations 1 and 7 . The results of one tetrapod with position 1 and those of one tetrapod with position 7 are presented.

Fig. 7 a) & 7 b) show the wave induced strain vs. the IRIBARREN-Parameter for position 1 and for quasi-static and dynamic load, respectively. The same relationship is shown in Fig. 7 c) & 7 d) for position 7. It appears that the maximum dynamic strain is an order of magnitude higher than the quasi-static one. However, both occur at the same IRIBARREN-parameter (I = 3.0).

4. First Results of Pendulum Tests

As shown in Fig. 1, pendulum tests have been performed on 1 kg- and 50 kg-Tetrapods with a reduced and a full cross-section, as well as on 250 kg - and 1.8 t - tetrapods with full cross-section.
A detailed description of the tests and some results have already been published (BÜRGER et al.,1989).

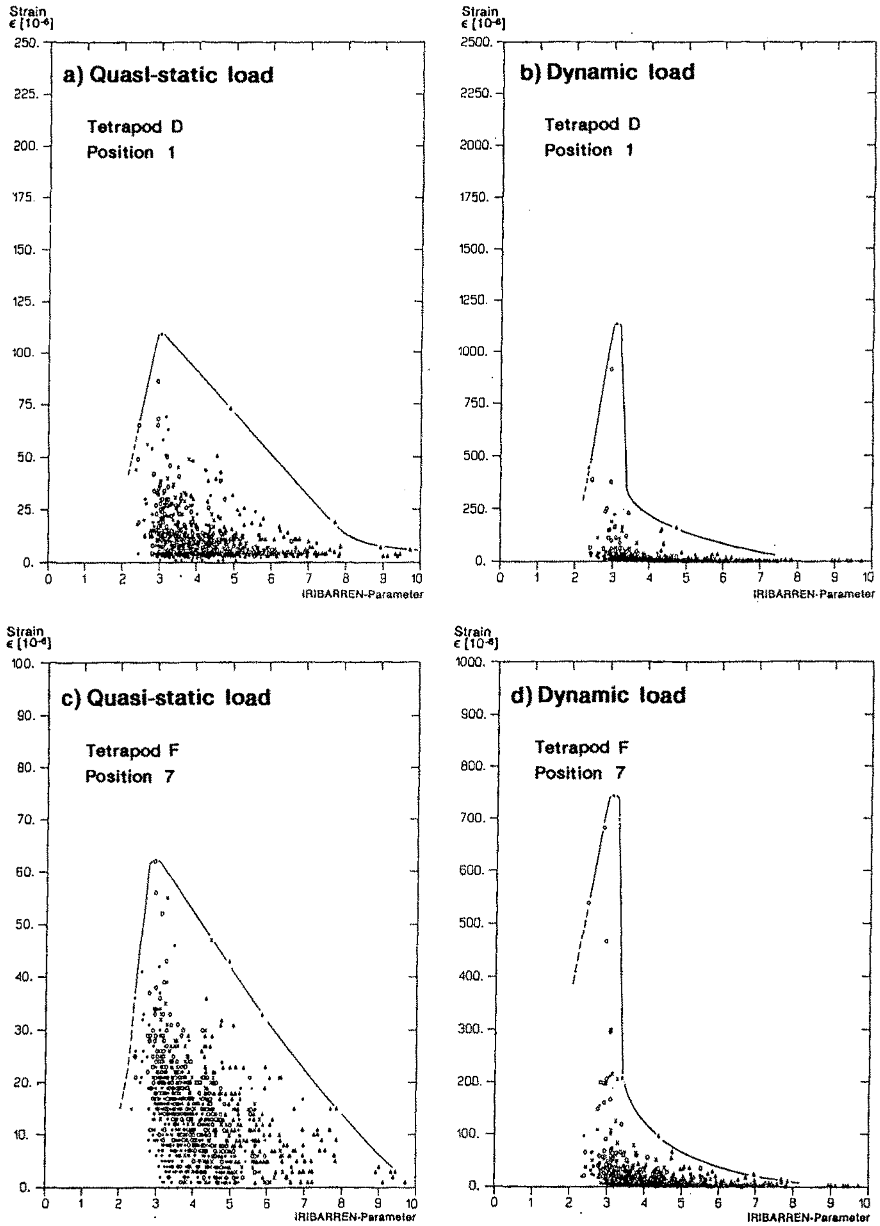


Fig. 7 Quasi-static and dynamic strain vs. IRIBARREN - Parameter (JONSWAP-Spectrum, H_S = 0.90 m, T_P = 4.5 s)

Considering the range of accuracy of the measurements and the range of the strain rate investigated ($\dot{\epsilon}$ = 0.061 to 1.0 s^{-1}) Fig. 8 suggests that a linear relationship between dynamic bending stress σ and impact velocity v appears to exist for the tested tetrapods (50 kg to 1.8 t); i.e. the following relationship holds:

$$\frac{\sigma_{T1.8}}{v_{T1.8}} = \frac{\sigma_{T250}}{v_{T250}} = \frac{\sigma_{T50}}{v_{T50}} \qquad (3)$$

where the indices T1.8, T250 and T50 refer to the 1.8 t, 250 kg- and 50 kg-tetrapods, respectively.

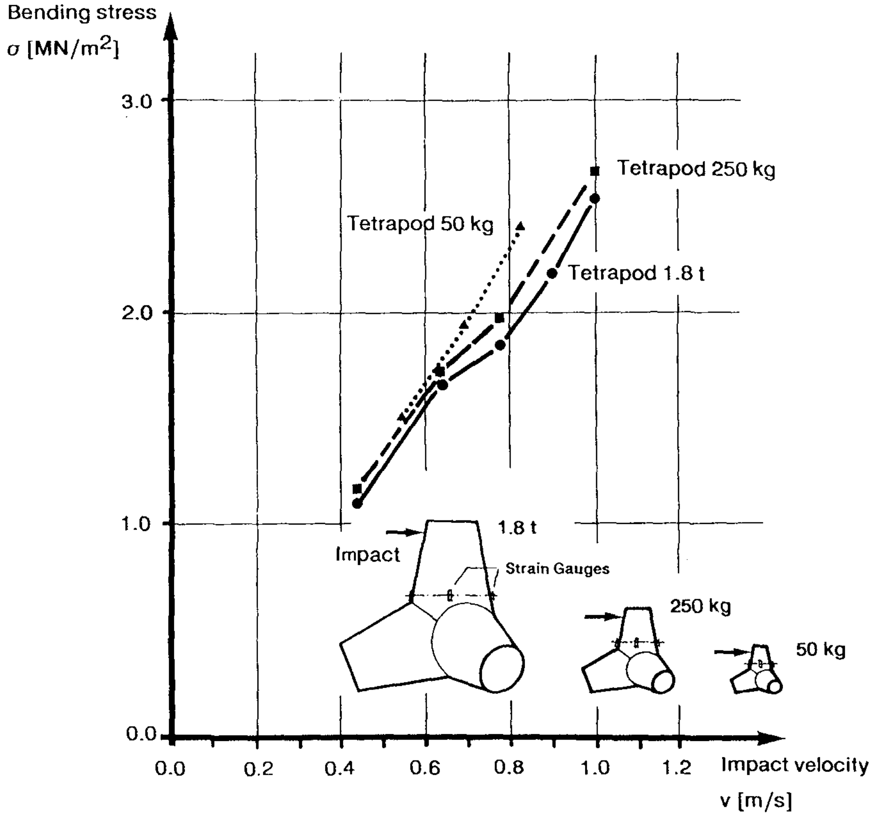


Fig. 8 Bending stress vs. impact velocity for the tested tetrapods

This supports the similitude criterium derived by NISHIGORI, et al. (1985) which suggests that the impact stress in the model (σ_m) is related to that in the prototype (σ_p) by:

$$\frac{\sigma_m}{\sigma_p} = \sqrt{\lambda} \tag{4}$$

where λ is the linear scale factor.

5. Perspectives

Within the scope of the ongoing analysis of the data it is planned to:

- clarify the similitude problems related to the transfer of the measured impact strains to prototype conditions;
- include the data related to static loading of the tetrapods in the analysis, so that the total loading can be assessed;
- elaborate a design procedure with respect to the structural stability of tetrapods based on the experimental results and on an extensive literature study.

6. References

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