A COMPLEX STUDY ON THE RELIABILITY ASSESSMENT OF THE CONTAINMENT OF A PWR

Part II. — Probabilistic Approach to Describe the Behaviour of Materials

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SUMMARY

It is well known that the response of any material depends strongly on the type of loading. In a conventional risk analysis materials properties such as strength or elastic modules are usually characterised by a mean value and a corresponding standard deviation. Critical situations of a reactor may be caused for instance by internal pressure, by earthquakes or by missiles. In the examples just mentioned the rate of loading varies by many orders of magnitude. Both mean value and variability of materials properties depend on the rate of loading. In addition the temperature plays an essential role. If these influences are neglected, results of a risk analysis are questionable. The sensitivity of a calculated probability of failure as determined with a simplified analysis is shown. As may have been anticipated both mean value $\bar{\sigma}$ and coefficient of variation V have a significant influence on the probability of failure.

Recently a comprehensive statistical analysis of steel properties as determined by the material testing laboratories of the German Federal Railways between 1949 and 1971 has been published. The coefficient of variation is found to be in the range of 3 to 8%, depending on shape and composition of the specimen. Within this range the probability of failure is extremely sensitive on a variation of this parameter.

A statistical analysis of tests carried out with special steel used for a reactor containment is presented. The coefficient of variation is in the same range as mentioned above. At elevated temperatures an increased coefficient of variation is observed. In all cases where the rate of loading is comparatively high, increased mean values for both tensile strength and yield stress have to be introduced in a realistic risk analysis. Corresponding values are presented and discussed.

In comparison with steel the concrete strength has a significantly higher variability. Under quasi-static loading conditions a large amount of experimental data is available from the literature. Nearly all critical conditions for the concrete hull, however, are characterized by higher rates of loading. It is shown that with increasing rate of loading mean values of strength and modules of elasticity increase in a similar way as pointed out in connection with properties of steel. A preliminary analysis of published test data indicates that the coefficient of variation decreases as the rate of loading increases. Hence the probability of failure under high rate of loading is positively affected by an increased mean value of strength and a decreased coefficient of variation.

This probabilistic approach to describe the mechanical behaviour of materials clearly points out that a realistic risk analysis necessarily has to be very complex.

1. Introduction

Any reliability analysis depends strongly on the entering load and resistance distribution functions. In this part of our composite contribution special emphasis is placed on the statistical aspects of the mechanical behaviour of steel and concrete. If relevant external load conditions such as plane crash or external pressure waves shall be taken into consideration the influence of rate of loading on strength of materials is a decisive parameter.

It is intended to describe the materials properties on the basis of a rather general statistical concept. In principle the basic assumptions must be applicable to a wide range of materials including steel and concrete. At this stage, however, the main interest is focused on the properties of concrete.

Usually a certain distribution function is used to characterize the mean value and the corresponding scatter of experimentally determined data such as strength or modulus of elasticity. Although this approach provides us with valuable information - hardly obtainable in another way - it is quite obvious that this means a serious simplification of the real situation. As more information on the actual materials behaviour becomes available simple distribution functions must be modified. More detailed information on the materials properties can also be taken into consideration by means of comprehensive simulation methods /1/. Being aware of this complexity the present paper may only be looked upon as being a preliminary and still simplified treatment.

Size effects are closely related to the variability of materials. There this aspect of probabilistic materials science will also be discussed here. Experimental data essentially supporting Weibull's approach are presented.

Assuming a given load spectrum the probability of failure is both dependent on the mean value and the variability of resistance. With the help of a sensitivity analysis it is possible to indicate the influence of a change of mean value or of variability on the probability of failure of a simple system. Characteristic relations are pointed out by using typical data of steel and concrete as examples.

This report describes first steps with the final aim to provide realistic data based on statistical concepts of material science for a structural reliability assessment. Elements of a method to determine the probability of failure of a steel containment by forming a statistical COD-concept are briefly outlined.

2. Theoretical Concepts

2.1 Random-pore and Monte Carlo-simulation

Concrete is a heterogeneous porous material. If an external load is applied to such a material a complicated threedimensional stress field is created within the specimen. The actually observed stresses depend on the

pore size and the pore geometry. A given material can be represented by a "random pore". The probability of occurrence of stresses around the random pore is the sum of all possible stress distributions around all critical pores /2,3/. At a certain stress level the probability of failure is given by the number of crossings of the created stress field with the barrier indicating the strength of the material.

Statistical behaviour of materials can also be described by means of Monte Carlo-simulation. Recently this approach has been used for studying crack propagation and failure process of concrete /4,5/.

So far the two above mentioned statistical concepts have only been used to describe the behaviour under quasi-static loading. A more comprehensive treatment will be outlined in the following section.

2.2 Stochastic theory for fracture of concrete

Usually statistical concepts deal with one material property, or with a single dependence only. Mihasi and Izumi /6/ presented a unified theoretical approach. Using Shanon's line graph they introduced three mathematical models. The first and simplest represents purely brittle fracture. This model is appropriate for hardened cement paste under tensile loading. The third model, rather meant for concrete, takes slow crack propagation into consideration. On the basis of the first model the probability that no fracture occurs before time t is given by:

$$D(t) = \exp\left\{-\int_0^t m L \sigma^\beta(t) dt\right\} \quad (1)$$

Where m stands for the number of elements and represents the size of a specimen and L is really a complicated expression describing the distribution of local stresses. L in fact has a similar meaning as the random pore introduced in the proceeding section. The external stress is called σ and β is just a materials parameter. Equ. (1) expresses directly creep fracture under sustained loading condition. The fracture probability is defined to be:

$$P(t) = 1 - D(t) \quad (2)$$

From this relation the probability density function of fracture is obtained:

$$p(\sigma) = \frac{d}{d\sigma} P(\sigma) \quad (3)$$

If a constant rate of loading is assumed ($\dot{\sigma} = \text{const}$) the mean value and variance are given by the following expressions:

$$f_d = \bar{\sigma} = \left(\frac{(1+\beta)\dot{\sigma}}{mL} \right)^{1/(1+\beta)} \cdot \Gamma\left(\frac{2+\beta}{1+\beta} \right) \quad (4)$$

$$V^2(\sigma) = \left(\frac{(1+\beta)\dot{\sigma}}{mL} \right)^{2/(1+\beta)} \cdot \left(\Gamma\left(\frac{3+\beta}{1+\beta} \right) - \Gamma^2\left(\frac{2+\beta}{1+\beta} \right) \right) \quad (5)$$

Where Γ is the gamma function. The strength increase with increasing rate of loading is pointed out by equ. (4). With increasing values of m and L strength decreases of course. As can be seen from equ. (5) the variance exhibits a

similar dependency. It is of special interest, however, to note that the coefficient of variation $\sqrt{2}/\bar{\sigma}$ does not depend on the rate of loading.

With equ. (4) the related mean value can be expressed as a function of the related stress rate:

$$f_d/f_s = \bar{\sigma}/\bar{\sigma}_0 = (\dot{\sigma}/\dot{\sigma}_0)^{1/(1+\beta)} = (T_0/T)^{1/(1+\beta)} \quad (6)$$

σ_0 and $\dot{\sigma}_0$ are reference mean value and reference rate of loading respectively. T_0 and T are similarly reference time to failure and actually observed time to failure under constant high rate of loading.

If a certain load is kept constant the following relation between stress level and time to failure T can be deduced:

$$f_d/f_s = \bar{\sigma}/\bar{\sigma}_0 = (T_0/T)^{1/\beta} \quad (7)$$

In equ. (7) T_0 represents the time to fracture in a short time experiment. The hardening of concrete counter-balances part of the stress decrease under sustained load. If this is taken into consideration equ. (7) has to be modified. A power law is a convenient way to do this:

$$f_d/f_s = \bar{\sigma}/\bar{\sigma}_0 = (T_0/T)^{1/\beta} ((T+T_1)/T_1)^{1/\alpha} \quad (8)$$

where T_1 is the age of loading.

The mathematical expressions derived by Mihasi and Izumi /6/ are only briefly presented here and shall be discussed in comparison with experimental data in the following sections.

3. Discussion of experimental results

3.1 Properties of concrete

3.1.1 High rate of loading

The mechanical behaviour of concrete under high rate of loading has been investigated by several authors. In Fig. 1 some typical results of experiments to determine the relative strength increase as function of rate of loading are compiled. In this Fig. only values for compressive strength of concrete have been entered /7,8,9,10/. It is not possible at the moment to explain the considerable divergence of experimental findings.

Takeda presented data which have been obtained under well defined conditions. Concrete slabs have been centrally loaded. Results of slabs with a thickness of 3 cm are shown in Fig. 2 and those of slabs with a thickness of 5 cm are shown in Fig. 3. Equ. (6) has been fitted to the experimental data. The solid line represents the relation of equ. (6) with $\beta = 12$ for the 3 cm slabs and $\beta = 13,5$ for the 5 cm slabs.

In Fig. 4 and Fig. 5 experimental data taken from /7/ and /8/ are shown. By fitting equ. (6) in this case higher values for β have been found. For

reasons of a more critical test of the unified statistical concept of Mihasi strength decrease under sustained load is also plotted in figures 4 and 5. This aspect, however, will be dealt with in the next paragraph. The dashed area in Fig. 5 gives a rough estimation of the scatter of experimental findings.

It is noteworthy that equ. (6) describes the dependence of strength under high rates of loading satisfactorily in a very wide range. By applying equ. (8) the range may even be extended to very low rates of loading or to sustained load.

The parameter β ($=m-1$) in equ. (9) and equ. (11) plays a dominant role in statistical materials science concepts. Therefore some data are compiled in Table I. Although a considerable scatter cannot be denied one may conclude that values derived from experiments with high rate of loading and from a completely different set of experiments i.e. behaviour under sustained load are reasonably close to one another. The unified statistical concept receives supplementary support if values of β as compiled in Table II are included in the discussion. These values have been obtained from tests with specimens of varying size, that means again a completely different experimental procedure.

It may be stated that the statistical concept of Mihasi and Izumi /6/ provides a realistic basis for a mathematical formulation of scatter of strength of concrete. There is enough experimental justification for a detailed application of this concept. The influence of rate of loading, size of specimen, and even temperature on the statistical behaviour can be satisfactorily described on this basis. There is an urgent need for further experimental results.

3.1.2 Sustained load

Long before the effect of high rate of loading on strength of concrete became of major interest the behaviour under sustained load has been studied both experimentally and theoretically. It can be shown that strength under sustained load can be interpreted approximately as strength under extremely low rates of loading. Therefore it is interesting to point out the link between these usually separately treated topics.

A detailed theoretical treatment of crack propagation on concrete under high load has been described in /13/. There are sufficient experimental data to check this approach. As shown in Fig. 4 and Fig. 5 the concept of Mihasi can be applied to describe the dependence of ultimate load in this range of rate of loading. Due to hardening which is caused by further hydration of loaded concrete the strength-curve increases at very low rates of loading. Thus this comprehensive approach describes the materials properties satisfactorily and covers more than ten decades of rate of loading.

3.1.3 Size effects

One of the early papers on the influence of diameter of fibres on tensile strength has been published by Griffith /14/. More than twenty years later Weibull provided a statistical theory of strength of solids /15/. The weakest-link concept necessarily implies that any strength distribution of a given population must follow an extreme value distribution function. It is hardly possible to justify in a convincing way any of the commonly used extreme value distribution functions /16/. After introducing some simplifying assumptions the fundamental formula of Weibull may be written as follows /17/:

$$P = 1 - \exp\left(-((\sigma - \sigma_u)/\sigma_o)^m\right) \quad (9)$$

In equ. (9) P is the probability of failure, σ the ultimate load and V the volume under stress. σ_u , σ_o and m are supposed to be materials properties. Equ. (9) and equ. (1) are both based on the concept of weakest link. Therefore m in equ. (9) is equivalent to $(1+\beta)$ in equ. (1). Obviously the mean value of strength $\bar{\sigma}$ corresponds to $P = 0,5$. For any particular P the following relation must be fulfilled if two specimens with different volume V are observed:

$$((\bar{\sigma}_1 - \sigma_u)/\sigma_o)^m V_1 = ((\bar{\sigma}_2 - \sigma_u)/\sigma_o)^m V_2 \quad (10)$$

If σ_u may be neglected a simple expression relating the mean value of strength to the corresponding volume is found:

$$(\bar{\sigma}_1/\bar{\sigma}_2)^m = V_2/V_1 \quad (11)$$

This well known relation can also be obtained in a more direct way from equ. (4). Weibull's theory has been successfully applied to describe rock failure /18/ and fracture of concrete /19/. In this report we will briefly report an experiment with hardened cement paste, the binding matrix in concrete. The flexural strength has been determined with prisms with a cross section of $4 \times 4 \text{ cm}^2$ and a length of 16 cm^2 at the age of 4 days. The volume has been changed by changing the position of loads of the four point bending test. Results for three different volumes are shown in Fig. 6. The solid lines are calculated by fitting equ. (9) to the experimental data. In this way σ_o was found to be 95 kp/cm^2 and $\sigma_u = 27 \text{ kp/cm}^2$ and $m = 8$.

In Fig. 7 the mean values of four different test series are shown as function of volume V . By applying equ. (11) m can be calculated. In this way a value of 14 is found. In Fig. 7 results of tensile tests are shown in addition. These specimens were 14 days old. In this case m is found to be 12.

It may be concluded that Weibull's extreme value distribution function represents experimental findings of hardened cement paste satisfactorily and that the important parameter m for hardened cement paste is close to ten. The age of loading and the type of loading (flexural or tensile) does not seem to have a significant influence.

3.1.4 Reinforced concrete

So far we have only discussed properties of plain concrete. In real structures, however, the situation is more complicated as we are faced with reinforced concrete. Generally it is rather difficult to predict the type of failure of a reinforced concrete specimen under high rate of loading or under impact load. Failure may occur under bending or under shear stress. Back surface spallation may damage the inner steel hull. Small projectiles may even penetrate.

Some experimental results of tests with reinforced concrete are described in /22/. An interesting attempt to optimize a reinforced concrete slab for a given impact load has been published by Burgess /23/.

More detailed information of the possible failure modes of reinforced concrete under high rate of loading and under impact load condition is of central importance for a realistic risk analysis. Moreover, it may well turn out that a layered structure of the concrete containment meets best the necessary requirements.

3.2 Properties of steel

3.2.1 Tensile strength and yield value

In several material testing laboratories of the German Federal Railways extensive tests have been carried out. Under the guidance of Petersen these data are being statistically analyzed. So far a preliminary report has been published /24/. Although some thousand test results are available the choice of a "correct" distribution function remains somewhat ambiguous. Significant differences can be observed between test results of different years. In 1971 the mean value of tensile strength for type St 37 has been determined to be $43,0 \text{ kp/mm}^2$ and the corresponding standard deviation $1,8 \text{ kp/mm}^2$. The equivalent values for type St 52 are $57,6$ and $2,43 \text{ kp/mm}^2$. The yield value has been found to be $28,3 \pm 1,9 \text{ kp/mm}^2$ and $40,2 \pm 2,3 \text{ kp/mm}^2$ respectively.

Results of tests of containment steel are also available. Because of obvious reasons the number of individual test results is much smaller. The difficulties involved in a statistical evaluation just mentioned in connection with the steel data of the German Federal Railway are therefore considerably enlarged. If in spite of all doubts a normal distribution is fitted the mean value of tensile strength at room temperature is found to be $68,2 \text{ kp/mm}^2$ with a corresponding standard deviation of $4,3 \text{ kp/mm}^2$. At 135°C a mean value of $62,5 \text{ kp/mm}^2$ and a standard deviation of $3,5 \text{ kp/mm}^2$ has been determined. A histogram of the experimentally determined yield values at room temperature is shown in Fig. 8. The fitted curve represents a mean value of $53,3 \text{ kp/mm}^2$ and a standard deviation of $1,9 \text{ kp/mm}^2$. In Fig. 9 analogous data but determined at 135°C are shown. Under these conditions the mean value decreases to $49,8 \text{ kp/mm}^2$ with a standard deviation of $2,7 \text{ kp/mm}^2$. The just mentioned data will be used in the numerical example in Part III of this contribution.

3.2.2 Elements of a concept to determine the probability of failure using COD-values

In a steel containment different types of flaws may occur. These defects may be categorized in different ways. A reasonable suggestion has been published in 1975 /25/. According to this report observed cracks and holes may be subdivided into three groups, i.e. through thickness flaws, surface flaws, and embedded flaws. From the actual defect dimensions a flaw parameter $\bar{a}$ can be deduced by taking into consideration the observed type of flaw. Another possibility would be the introduction of a "random pore" similar to the random pore as described in section 2.1.

In Fig. 10 an assumed probability distribution of flaw parameter $\bar{a}$ is schematically shown. If a certain load σ is applied to a system having the flaw distribution P_1 a characteristic distribution function P_2 for the resulting crack opening displacements δ can be calculated. The distribution of the values of critical crack opening displacements δ_c is assumed to be a materials property such as the distribution function of yield value and strength. Then the probability of failure may be calculated by solving the well known convolution integral /26/. The classical statistical method of evaluating the convolution integral will be used in Part III of the present contribution.

4. Sensitivity analysis

If the convolution integral of the load spectrum and the resistance spectrum is calculated the probability of failure of a given system is obtained, as mentioned above. Here it shall be used to investigate separately the influence of a change of mean value and coefficient of variation on the probability of failure. We are aware of the fact that this method implies trenchant simplifications and it shall only be used to point out some trends.

In Part I of this contribution the stress distribution in the steel hull of the secondary containment caused by a LOCA is estimated. Using this load spectrum the probability $P_f (= 10^{-Y})$ that the yield value is reached has been calculated. In Fig. 11 the probability of failure is plotted as a function of the coefficient of variation. Four different mean values have been used as parameter. If the coefficient of variation is small, let us say below 5 %, a small increase of the mean value has a tremendous influence on the probability of failure. If a material with a large coefficient of variation is used an increase of the mean value has a comparative small effect. This result may contribute to an economized use of materials.

A similar analysis has been carried out with characteristic values of concrete. The result is shown in a somewhat different way in Fig. 12. Here the probability of failure $P_f = 10^{-Y}$ is plotted versus the ratio of mean strength and mean load. The indicated example shows that if the coefficient of variation (used as parameter in Fig. 12) is 17 % a large increase of the mean strength has little effect on the probability of failure (see A→B). In contrast the

probability of failure is extremely sensitive with regard to a change of the mean strength if the coefficient of variation is only 8 % (see $A' \rightarrow B'$). This means that the strengthening effect under high rate of loading is only beneficial for the safety of a structure if the coefficient of variation does not exceed a certain level. If, however, the coefficient of variation is increased by the type of loading an overall increase of the probability of failure may result (see $A \rightarrow C$ and $A' \rightarrow C'$) even so the mean value of resistance is increased.

5. Concluding remarks

A unified statistical method to describe the mechanical behaviour of materials is presented. On this basis fundamental equations for mean value and coefficient of variation are obtained. The application of statistical methods is limited by a lack of reliable experimental data. More knowledge on probable failure modes of reinforced concrete is needed for a realistic risk analysis.

References

- /1/ BECHER, P.E. "Probability of failure of a BWR steel pressure vessel" Ispra courses, Reliability Engineering, STR/14/76 (1976)
- /2/ ZAITSEV, J.W. and WITTMANN, F.H., "A statistical approach to the study of the mechanical behaviour of porous materials under multiaxial state of stress" Proc. of the 1973 Symposium on Mechanical Behaviour of Materials, Kyoto, Japan, p. 105 (1974)
- /3/ ZAITSEV, J.W. and WITTMANN, F.H., "Eine theoretische Studie des Verhaltens von Beton unter kurzzeitiger ein- und zweiachsiger Belastung", Materialprüf. 16, 170 (1974)
- /4/ ZAITSEV, J.W. and WITTMANN, F.H., "Crack propagation and fracture of a twophase material such as concrete", contribution to the International Conference on Fracture 1977, Waterloo (1977)
- /5/ WITTMANN, F.H. and ZAITSEV, J.W., "Concrete - a viscoelastic porous body", Proc. Second International Conference on Mechanical Behaviour of Materials, Boston, p. 163 (1976)
- /6/ MIHASI, H. and IZUMI, M., "A stochastic theory for concrete fracture", Cement and Concrete Research, 7, (1977)
- /7/ WATSTEIN, D., "Effect of straining rate on the compressive strength and elastic properties of concrete, "Amer. Concr. Inst., 49, 729, (1953)
- /8/ HUGHES, B.P., and GREGORY, R., "Concrete subject to high rates of loading in compression", Mag. Concr. Research, 24, 25 (1972)
- /9/ SPARKS, P.R., and MENZIES, J.B., "The effect of rate of loading on plain concrete", Mag. Concr. Research, 25, 73 (1973)

- /10/ EVANS, R.H., "Effect of rate of loading on the mechanical properties of some materials", J. Inst. Civil Engin. 18, 296 (1942)
- /11/ TAKEDA, J., TACHIKAWA, H., FUJIMOTO, K., "Influences of straining rate and propagating stress waves on deformation and fracture of concrete", Proc. Second Internat. Conf. on Mechanical Behaviour of Materials, Boston p. 1468 (1976)
- /12/ RÜSCH, H., SELL, R., RASCH, C., GRASSER, E., HUMMEL, A., WESCHE, K., and FLATTEN, H., "Festigkeit und Verformung von unbewehrtem Beton unter konstanter Dauerlast". Deutscher Ausschuß für Stahlbeton, Heft 198 (1968)
- /13/ WITTMANN, F.H. and ZAITSEV, J., "Verformung und Bruchvorgang poröser Baustoffe bei kurzzeitiger Belastung und Dauerlast". Deutscher Ausschuß für Stahlbeton, Heft 198 (1968)
- /14/ GRIFFITH, A.A., "The phenomenon of rupture and flow in solids", Phil. Trans. Roy. Soc. 221 A, 163 - 198 (1920)
- /15/ WEIBULL, W., "A statistical theory of the strength of materials", Ing. Vetenskaps Akad. Handl. 151, 5 - 44 (1939)
- /16/ SAIBEL, E., "Size effects in fracture", Proc. Int. Conf. on Structure, Solid Mechanics and Engineering design in Civil Engineering Materials, Southampton, part 1, p. 125 (1969)
- /17/ WEIBULL, W., "The phenomenon of rupture in solids", Ing. Vetenskaps Akad. Handl. 153, 5 - 55 (1939)
- /18/ HUDSON, J.A., and FAIRHURST, C., "Tensile strength, Weibull's theory and a general statistical approach to rock failure", Proc. Int. Conf. on Structure, Solid Mechanics and Engineering design in Civil Engineering Materials, Southampton, part 1, p. 901 (1969)
- /19/ SABNIS, G.M. and ARONI S., "Size effects in material systems - the state of the art", Proc. Int. Conf. on Structure, Solid Mechanics and Engineering Materials, Southampton, part 1, p. 131 (1969)
- /20/ SPETLA, Z., "Einfluß der Schlankheit, Größe und Gestalt der Prüfkörper auf die Zugfestigkeit des Betons", Wissenschaft. Zeitung der TU-Dresden 17, 1552-1554 (1968)
- /21/ HOLIDAY, E., "Composite Materials", Elsevier Publ. Comp. (1966)
- /22/ SKOV, K., and OLESEN, S.Ø. "Impact resistance of reinforced and pre-stressed concrete members", Mat. et Constr. 8, 116-125 (1975)
- /23/ BURGESS, W.M., and CAMPBELL-ALLEN, D., "Impact resistance of reinforced concrete as a problem of containment", Research Report Nr R 251, The University of Sydney (1974)
- /24/ PETERSEN, Chr., and HAWRANEK, R., "Zur Sicherheitstheorie im konstruktiven Stahlbau", Arbeitsberichte zur Sicherheitstheorie der Bauwerke, Heft 5 (1974)
- /25/ N.N., "Proposed Assessment Methods for Flaws with Respect to Failure by Brittle Fracture", Welding in the World 13, 29-48 (1975)
- /26/ FREUDENTHAL, A.M., GARRELTS, J.M., and SHINOZUKA, M., "The Analysis of Structural Safety", J. Struct. Div. Proc. ASCE, 92, 267-325 (1966)

Table I
Parameter β as determined from experiments
with high rate of loading (equ.(6)) and
under sustained load (equ.(8)).

material	type of loading	state of stress	$\beta = m-1$	Lit.
concrete	high	flex.	12-14	/11/
"	rate	comp.	25-30	/7/
"	of	comp.	17-35	/8/
"	loading	comp.	25-40	/9/
"	sus-	comp.	25	/12/
"	tained	comp.	21	/13/
h.cement-	load	comp.	25	/13/
paste				

Table II
Parameter m as determined with the help of
equ.(11).The last value has been determined
by applying equ.(9).

material	state of stress	$m = 1+\beta$	Lit.
concrete	flex.	12.5	/19/
"	tens.	24-47	/20/
"	comp.	27	/21/
h.cement-	flex.	14	-
paste	tens.	12	-
"	flex.	8	-

Fig. 1 : Related compressive strength of concrete as function of related rate of loading, according various authors: (1) Watstein /7/, (2) Hughes and Gregory /8/, (3) Sparks and Menzies /9/, (4) Evans /10/.

Fig. 2 : Related flexural strength of concrete slabs with a thickness of 3 cm as function of related rate of loading as determined by Takeda /11/. The solid line is calculated using equ. (6) with $\beta = 12$.

Fig. 3 : Related flexural strength of concrete slabs with a thickness of 5 cm as function of related rate of loading as determined by Takeda /11/. The solid line is calculated using equ. (6) with $\beta = 13,5$.

Fig. 4 : An attempt to describe simultaneously the behaviour under sustained load and under high rates of loading. The solid line is calculated by using equ. (6) and equ. (8) respectively. Experimental data are taken from the literature: sustained load /12/ and high rate of loading /7/.

Fig. 5 : An attempt to describe simultaneously the behaviour under sustained load and under high rates of loading. The solid line is calculated by using equ. (6) and equ. (8) respectively. Experimental data are taken from the literature: sustained load /13/ and high rate of loading /8/.

Fig. 6 : Probability of failure of hardened cement paste under compression. The volume of the specimens has been varied between 24 and 112 cm³. Solid lines are calculated using equ. (9).

Fig. 7 : Mean value of flexural and tensile strength of hardened cement paste as function of volume. A solid line is fitted using equ. (11).

Fig. 8 : Frequency distribution of the yield value of containment steel FG 47 W at 22 C. Mean value = 53,3 kp/mm² and standard deviation = 1,88kp/mm².

Fig. 9 : Frequency distribution of the yield value of containment steel FG 47 W at 135 C. Mean value = 49,8 kp/mm² and standard deviation = 2,7 kp/mm².

Fig. 10 :

Schematic representation of the reliability assessment of a steel containment using the COD-concept. P_1 is the probability distribution of the flaw size parameter and P_2 is the probability distribution of corresponding COD-values assuming a certain external stress level.

Fig. 11 :

Probability of failure ($P_f = 10^{-Y}$) as function of coefficient of variation V_y of yield point of steel. The mean yield value is indicated as a parameter.

Fig. 12 :

Probability of compressive failure ($P_f = 10^{-Y}$) of concrete as function of the ratio μ of mean value of resistance and mean value of load. The coefficient of variation is indicated as a parameter. By a certain increase of μ the corresponding decrease of probability of failure is strongly dependent on the coefficient of variation. This is shown by lines $A \rightarrow B$ and $A' \rightarrow B'$. If an increase of μ is accompanied by an increase of coefficient of variation, the probability of failure may even increase as shown schematically by the lines $A \rightarrow C$ and $A' \rightarrow C'$.