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# On Ship Reliability and Safety

## by



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1- "Safety Assurance: Methods of Assessment for Ship Structures", IMAEM, September, (Italy-1981), Trieste, Second Conference, Shama, M. A.,

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# SAFETY ASSURANCE:

# METHODS OF ASSESSMENT FOR SHIP STRUCTURES

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# SAFETY ASSURANCE; METHODS OF ASSESSMENT FOR SHIP STRUCTURES

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## S U M M A R Y

The main causes of failure of marine structures are indicated. Particular emphasis is placed on the failure resulting from the extreme values of load and strength. The full- and semi- probabilistic approaches to safety assurance of marine structures are examined. The various methods of calculating the probability of failure are given. The strength and load factors, associated with the partial safety factor approach, are especially considered. The effect on structural reliability of the deterioration of structural capability with time, assumed density function and the degree of truncation of the density function are indicated. The importance of truncating the density functions of both loading and strength is stressed.

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $F_x(x)$ | = | cumulative distribution function |
| $f_x(x)$ | = | density function (truncated) |
| k, K | = | constants |
| m, M | = | margin of safety |
| $\bar{m}$ | = | mean value of M |
| $P_f$ | = | probability of failure |
| p.d.f. | = | probability density function = $p_X(x)$ |
| q, Q | = | loading, demand |
| $Q_k$ | = | characteristic value of Q |
| $\bar{q}$ | = | mean value of Q |
| r, R | = | resistance, capability |
| $R_k$ | = | characteristic value of R |
| $\bar{r}$ | = | mean value of R |
| $v_X$ | = | coefficient of variation X |
| $\beta$ | = | safety index |
| $\gamma$ | = | overall safety factor |
| $\gamma_Q$ | = | load factor |
| $\gamma_R$ | = | strength factor |
| $\bar{\gamma}$ | = | central safety factors |
| $\sigma_X$ | = | standard deviation of X |
| $\lambda, \nu$ | = | specified small values |
| $\phi(x)$ | = | tabulated cumulative probability of the standard normal variate X for $X \leq x$ |

Safety is today concerned not only with the structure itself, but also with external damage that may result as a consequence of failure. Therefore, safety is not an absolute measure and should be related to the economic and social consequences of failure.

The fundamental equation for safety assurance is given by:

$$R > Q \qquad (1)$$

This equation could be given in terms of either the margin of safety M:

$$M = R - Q > 0 \qquad (2)$$

or the "total factor of safety" $\gamma$ :

$$\gamma = R/Q > 1.0 \qquad (3)$$

The load, Q, normally refers to the maximum value of loading likely to occur over the expected service life of a ship. The load generally varies over a wide spectrum, whose lower limit could be assumed zero. The upper limit should be carefully estimated as it has a significant effect on safety and economy (2).

The resistance, R, is the limitng state beyond which the structure is expected to fail, to be damaged or collapse. The variability of R reuslts from the variabilities of the mechanical properties of the material, dimensional tolerances, fabrication defects, residual stresses, initial distortions, occuracy of stress analysis, errors in mathematical modelling, corrosion, wear and tear, etc.

The resistance should vary over a narrow spectrum. The lower limit represents the critical value regarding failure and the upper limit indicates some degree of overdesign which has an impairing effect on economy.

Therefore, in order to ensure an acceptable safety margin, or degree of risk, the lower limit of resistance and the upper limit of load should be carefully examined and controlled.

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## 2.1. Responsible Authorities

Classification societies remain the main authority responsible for the assurance of safety for ships and marine structures. The methods commonly used are:

i- control design by specifying procedures and constraints;

ii- provision of corrosion margin to compensate for material deterioration and ensure adequate strength;

iii- control quality of material and construction;

iv- control quality of maintenance and repair by regular and special surveys.

For conventional ships, the classification society rules are based on long experience and gradual development. They ensure an acceptable safety level of the structural performance. Structural reliability is based on data collected from ships in service, such as damage statistics. These statistical data are usually condensed and then treated deterministically for developing rules for the structural design of ships. In this deterministic approach, safety assurance is based on the irrational concept of the "safety factor". Because of the inconsistancy and lack of uniformity of these safety factors, marine structures designed according to these rules are generally overdesigned. For unconventional marine structures, such as "offshore structures", the extrapolation from available data may be extremely difficult. Therefore, a rational procedure is required for assessing and checking structural safety.

# 3. RATIONAL APPROACH

In this rational approach, safety assurance should be based on the statistical parameters of both loading and strength. It is evident that neither the load "Q" nor the strength "R" can be represented by a single value. Both are functions of several random variables and can only be treated statistically. The "demand", Q, normally refers to the maximum value of loading likely to occur over the expected service life of a ship. The resistance (strength), or capability, represents a limiting state beyond which the structure is expected to fail or collapse.

However, this probabilistic approach could be divided into two methods (1, 3):

i- Full-statistical method (normally called level-3 method)
In this method, safety assurance is based on a complete probabilistic analysis for the whole structural system, or elements. The full probabilistic information of both load and resistance is required, together with the target failure probabilities.

ii- Semi-statistical method
This method is generally divided into two levels:

a- Safety index approach (level-2 method)
Structural safety is ensured by a safety index compatible with acceptable probability of failure.

b- Partial safety factor approach (level-1 method)
Structural safety is ensured by a number of partial safety factors, taking account of the variation of maximum loading and minimum strength.

In the following analysis, these three methods are considered in more detail.

## 3.1- Full-statistical method

This method is based on the estimation of the probability of failure, $p_f$, or the risk, for the particular mode of failure under investigation, using the p.d.f. of both load and resistance of the whole structure, or any part of it.

For the present state of affairs, it is economically unjustifiable and technologically unfeasible to determine "exactly" the p.d.f.'s of both Q and R, for the whole structure and for various modes of failure. Therefore, for practical applications, the full probabilistic method may be used only for one element of the structure and also for one particular mode of failure. In this case, $p_f$ is given by:

$$p_f = \int_{-\infty}^{\infty} p_{R,Q}\left\{r,(m - r)\right\} dr \qquad (4)$$

When R and Q are statistically independent, $p_f$ is given by:

$$p_f = \int_0^\infty F_R(q)p_Q(q)dq = \int_0^\infty (1 - F_Q(r))p_R(r)dr \qquad (5)$$

where: $F_X(x) = P(X < x) = \int_0^x p_X(u)du \quad , \; X = R,Q$

The probability of failure, $p_f$, is the shaded area shown in fig. (1). It is necessary here to identify the difference between the probability of failure due to collapse and the probability of failure due to damage. The former is generally less than the latter, as shown in fig. (1).

### 3.1.1. Calculation of $p_f$

The calculation of $p_f$ could be performed using equation (5), when the p.d.f.'s of both R and Q are known apriori. For the particular case when both R and Q have normal distribution functions, $p_f$ is given by:

$$p_f = 1 - \phi\left\{(\bar{r} - \bar{q})/\sqrt{\sigma_R^2 + \sigma_Q^2}\right\} \qquad (6)$$

where: $\bar{r}$, $\bar{q}$, $\sigma_R$ and $\sigma_Q$ are the means and standard deviations of R and Q respectively.

However, for non-normal density function, the calculation of $p_f$ becomes rather tedious and requires numerical approximations. One solution to this problem is based on fig. (2) and the following approach (2):

Let: $U = \int_r^\infty p_Q(q)dq \quad , \quad dV = p_R(r)dr$

Then $$p_f = \int_0^1 U dV \qquad (7)$$

This integration could be performed numerically using Simpson's Rule (2).

An alternative approach for calculating $p_f$ could be based on the p.d.f. of the margin of safety M.

In this case, $p_f$ is given by:

$$p_f = P(R < Q) = \int_{-\infty}^{0} p_M(m)dm \qquad (8)$$

It should be realised that the assertion "the probability of failure" equal "x" is meaningless in itself. $p_f$ acquires meaning only as a relative characteristic for estimating the structural reliability of various arrangements and configurations of the same structure, or of the same structure under different loading conditions.

3.1.2- Estimation of the mean value of resistance

For a particular mode of failure and a specified value of $p_f$, the required mean value of R, for given statistical parameters of the load, is given by:

$$\bar{r} \geqslant \bar{q} + \sqrt{\sigma_R^2 + \sigma_Q^2} \cdot \phi^{-1}(1 - p_f) \qquad (9)$$

As an example illustrating the use of equation (9), assume that:

$$Q \equiv N\,(2.0,\ 0.1) \quad MN$$
$$\sigma_R = 0.1 \quad MN$$
$$p_f = 1 \times 10^{-3}$$

Then, the required minimum mean value of R is given by:

$$\bar{r} \geqslant 2.0 + \sqrt{0.1^2 + 0.1^2}\ \phi^{-1}(0.999)$$
$$\geqslant 2.42 \quad MN$$

When both R and Q are log-normally distributed, the required mean resistance is given by:

$$\bar{r} \geqslant \bar{q}.\exp(\sqrt{v_R^2 + v_Q^2} . \phi^{-1}(1 - p_f)) \qquad (10)$$

### 3.2- The Safety Index Approach

In this approach, only the statistical parameters of the p.d.f.'s of R and Q are required (the means and standard deviations). Assuming that R and Q are statistically independent, the mean and variance of the margin of safety M could be derived from the corresponding values of R and Q as follows:

$$M = R - Q$$
$$\bar{m} = \bar{r} - \bar{q} \qquad (11)$$
$$\sigma_M^2 = \sigma_R^2 + \sigma_Q^2$$

In this case, structural safety is defined in terms of a safety index $\beta$ :

$$\beta = \bar{m} / \sigma_M = (\bar{r} - \bar{q}) / \sqrt{\sigma_R^2 + \sigma_Q^2} \qquad (12)$$

It is evident that $\beta$, see fig. (3), depends on the means and standard deviations of R and Q.

In the general case, R and Q are nonlinear functions of several random variables:

$$R = R\,(x_1, x_2 \dots x_n), \qquad Q = Q\,(y_1, y_2, \dots y_m)$$

In this case, R and Q may be determined by expanding their functions in a power series in the neighbourhood of their mean values. For some cases, R and Q may be linearised by neglecting the nonlinear terms. The mean and variance can be approximated by:

$$\bar{r} = R(\bar{x}_1, \bar{x}_2, \dots \bar{x}_n)\ ,\ \bar{q} = Q(\bar{y}_1, \bar{y}_2, \dots \bar{y}_m) \qquad (13)$$

$$\sigma_R^2 = \sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i}\right)^2 . \sigma_{x_i}^2 \quad , \quad \sigma_Q^2 = \sum_{j=1}^{m} \left(\frac{\partial Q}{\partial y_j}\right)^2 . \sigma_{y_j}^2 \qquad (14)$$

The coefficient of variation can be also approximated by:

$$v_X^2 = \sum_{j=1}^{k} \left( \frac{\partial X}{\partial z_j} \cdot \frac{\bar{z}_j}{\bar{x}} \right)^2 . v_{z_j}^2 \qquad (15)$$

The effect of neglecting the non-linear terms on the magnitudes of the means and variances has not been fully quantified.

The safety index $\beta$ could be also given in terms of the coefficients of variation $v_R$ and $v_Q$ and the central safety factor $\bar{\gamma}$ as follows:

$$\beta = (\bar{\gamma} - 1) / \sqrt{v_R^2 \; \bar{\gamma}^2 + v_Q^2} \tag{16}$$

3.2.1- <u>Limiting values of mean and coefficient of variation of resistance:</u>

The limiting values of mean resistance for a particular mode of failure and a specified value of the safety index $\beta_o$ could be given in terms of the mean load and the variances of load and resistance as follows:

$$\bar{r} \geq \bar{q} + \beta_o \sqrt{\sigma_R^2 + \sigma_Q^2} \tag{17}$$

Similarly, the limiting coefficient of variation of resistance, $v_R$, for a specified safety index $\beta_o$, central safety factor $\bar{\gamma}$ and the coefficient of variation of loading $v_Q$, could be estimated as follows:

$$v_R \leq \frac{1}{\bar{\gamma}} \cdot \sqrt{\left(\frac{\bar{\gamma} - 1}{\beta_o}\right)^2 - v_Q^2} \tag{18}$$

3.2.2- <u>The Target Safety Index</u>

The selection of the target safety index $\beta_o$ should be based on the type of loading (static, dynamic), mode of failure (damage, collapse) and the consequences of failure (danger to human life, economy or both).

For ship hull girders, the target safety index should depend on ship type and length, as given by Faulkner (3).

It is evident that when the p.d.f. of the margin of safety M is normal, the probability of failure could be determined using the safety index $\beta$ as follows:

$$P_f = 1 - \phi(\beta) \tag{19}$$

## 3.3. The partial Safety Factor Approach

In this approach, structural safety is ensured by a number of safety factors, which take account of the variabilities of load and resistance.

The fundamental equation of safety assurance is given by:

$$R \geqslant \gamma Q \qquad (20)$$

where $\gamma$ = total safety factor

This equation could be given in terms of the mean values of load and resistance as follows:

$$\bar{r} \geqslant \bar{\gamma}\,\bar{q} \qquad (21)$$

The central safety factor could be given in terms of the strength and load factors as follows:

$$\bar{\gamma} = \gamma_r \cdot \gamma_q \qquad (22)$$

$\gamma_r$ and $\gamma_q$ take account of the variabilities of resistance and load respectively.

Using the formulation given by equation (17) and the approximation given in reference (4), i.e.

$$\sqrt{\sigma_R^2 + \sigma_Q^2} \simeq 0.75(\sigma_R + \sigma_Q) \qquad (23)$$

the partial safety factors, $\gamma_r$ and $\gamma_q$ could be given in terms of the coefficients of variation and the specified safety index $\beta_o$ as follows:

$$\gamma_r = 1/(1 - 0.75\beta_o v_R) \qquad (24)$$

$$\gamma_q = 1 + 0.75\,\beta_o v_Q \qquad (25)$$

Similarly, equation (20) could be given in terms of the characteristic values of load and resistance, $R_k$ and $Q_k$, as follows:

.../..

see fig. (4):

$$R_k \geqslant \gamma_k \; Q_k \qquad (26)$$

where: $\gamma_k = \gamma_R \cdot \gamma_Q$

$$R_k = \bar{r}\,(1 - k_R . v_R) \qquad (27)$$

$$Q_k = \bar{q}\,(1 + k_Q . v_Q)$$

When both R and Q are normally distributed, the partial safety factors, $\gamma_R$ and $\gamma_Q$, are given by:

$$\gamma_R \simeq (1 - k_R v_R)/(1 - 0.75 \beta_o \; v_R)$$

$$(28)$$

$$\gamma_Q \simeq (1 + 0.75 \beta_o v_Q)/(1 + k_Q v_Q)$$

Also, when R and Q are log-normally distributed, $\gamma_R$ and $\gamma_Q$ are given by:

$$\gamma_R \simeq \exp - \left\{ (0.75 \quad - k_R) v_R \right\}$$

$$\gamma_Q \simeq \exp \; \left\{ (0.75 \; - \; k_Q) v_Q \right\}$$

It should be noted that equation (20) could be also given in terms of $\gamma_X$ and $\gamma_Y$. The former takes account of the factors causing failure and the latter depends on the consequences of failure. By introducing rating factors (5), it is possible to estimate the partial safety factors.

3.3.1- Example

Consider the following case:

$v_R = v_Q = 0.1$

$k_R = k_Q = 2.5$ , $\beta = 4.0$

i- R and Q are normally distributed

| | | |
|---|---|---|
| $\gamma_R = 1.072$ | $\gamma_Q = 1.04$ | $\gamma_k = 1.115$ |
| $\gamma_r = 1.43$ | $\gamma_q = 1.3$ | $\gamma = 1.857$ |

ii- R and Q are log=nroamlly distributed

| | | |
|---|---|---|
| $\gamma_R = 1.053$ | $\gamma_Q = 1.05$ | $\gamma_k = 1.105$ |

.../..

## 4. FACTORS AFFECTING THE PROBABILITY OF FAILURE

The probability of failure is a characteristic of the structural system, or an element of this system, for the particular mode of failure and under the particular loading system. Its magnitude is influenced by the following factors.

i) Deterioration of structural capability with time.

Structural capability deteriorates with time as a result of corrosion, damage accumulation, etc. see fig. (5). Therefore, the ability of a structure to maintain its original level of structural efficiency over its service life can be significantly improved by corrosion control, using materials having good corrosion resistance, minimization of surface area, provision of good drainage, access for cleaning, access for inspection, painting, etc.

ii) Assumed density functions.

Since $p_f$ depends mainly on the shape of the upper tail of the loading function and the lower tail of the resistance function, its magnitude will be very sensitive to the type of functions assumed, see fig. (6).

iii) Degree of truncation.

Structural capability cannot vary from $-\infty$ to $+\infty$ or even attain zero values (6). Therefore, the p.d.f. of R should be truncated on both sides of the p.d.f. Similarly, the loading cannot attain infinite values. The p.d.f. of Q should be also truncated, at least at its upper tail. The truncated density function could be derived from the assumed theoretical p.d.f. as follows:

Let $p_X(x)$ = p.d.f. of X

$f_X(x)$ = p.d.f. after truncation, $x_l \leqslant X \leqslant x_u$

$x_l, x_u$ = lower and upper feasible limits of X.

Then the truncated density function is given by (7):

$$f_X(x) = p_X(x)/H \qquad (29)$$

.../..

and the cumulative distribution function is given by:

$$G_X(x) = (F_X(x) - F_X(x_1))/H \qquad (30)$$

where: $$H = \int_{x_1}^{x_u} p_X(x)dx = F_X(x_u) - F_X(x_1) \qquad (31)$$

It should be realised that it is possible to reduce the extreme loads by using suitable control measures (8). The resulting truncation of the demand distribution function should improve structural design without impairing structural reliability, Similar results could be obtained by controlling the factors imparing structural capability. Therefore, hull steel weight could be reduced without reducing structural safety.

In the calculation of $p_f$, it is not necessary to use truncated density function except when the control measures adopted are effective. The error resulting from neglecting the effect of truncation is examined in reference (2).

## 5. CONCLUSIONS

The main conclusions drawn up from this investigation could be summarised as follows:

i- The rationalisation of ship structural design should be based not only on the estimated values of load and resistance but also on their expected variabilities. Therefore, the statistical methods and theory of probability are very powerful tools for the rationalisation process.

ii- The probability of failure, for any particular mode of failure, should be treated as a relative characteristic of the structural system and should be used only as a qualitative measure for comparing alternative designs, or different conditions of the same design.

.../..

iii- The probability of failure could be reduced by truncating the density functions of both load and strength, using reliable and economical control methods.

iv- The methods used for assessing structural reliability, due to extreme values of load and resistance, should be considered with a realistic outlook. The degree of sophistication of the method used should be based on the expected frequency and consequences of failure.

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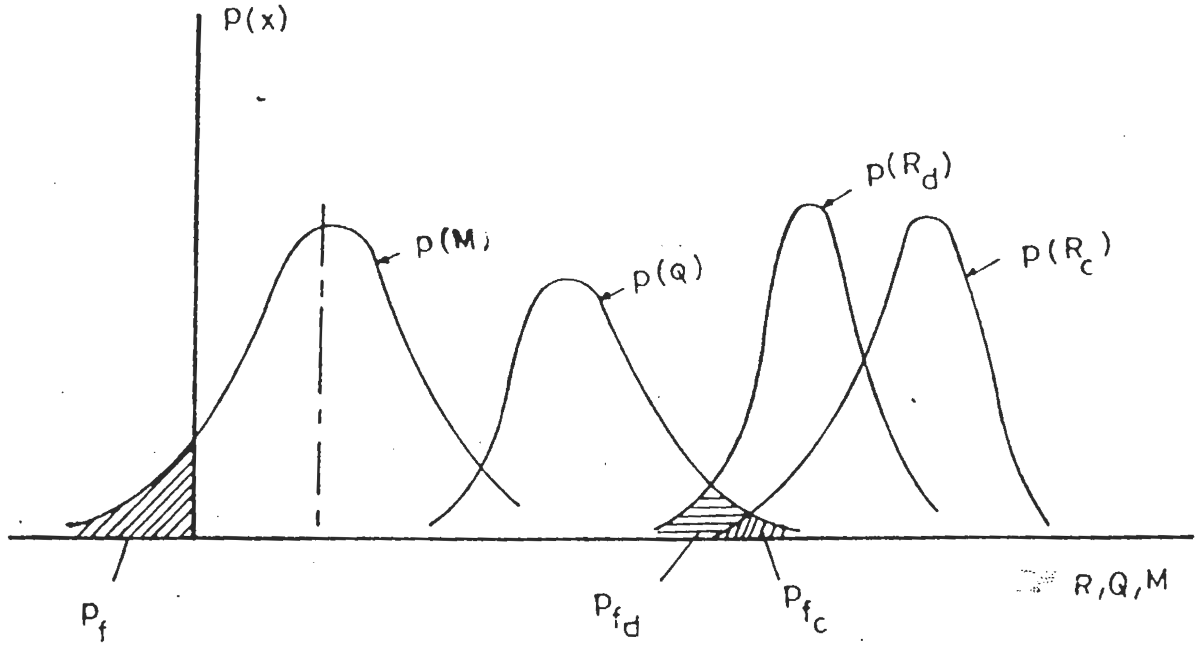



Fig (1). Probability of Failure, Damage, Collapse

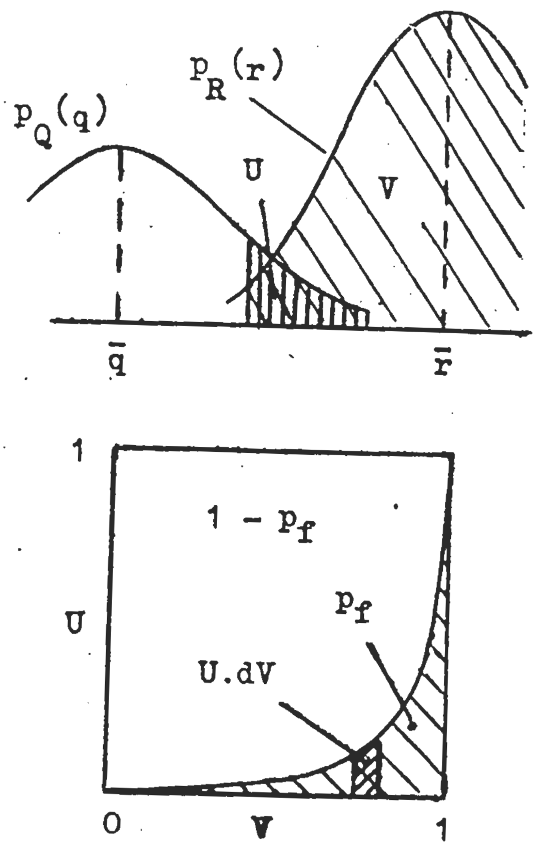



Fig.(2). PROBABILITY OF FAILURE

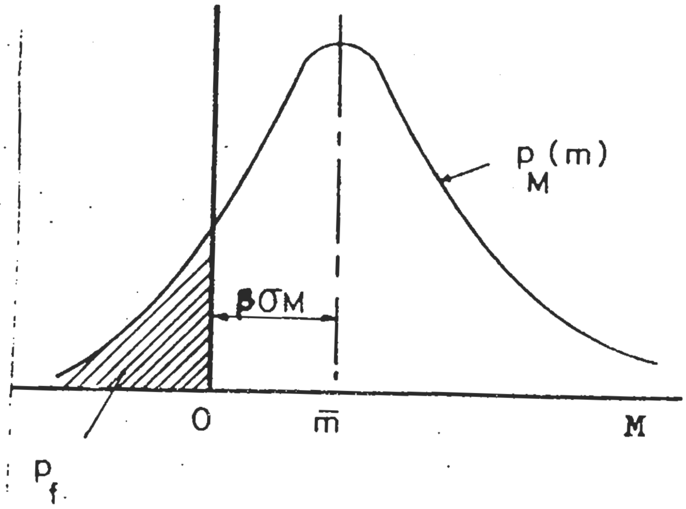



Fig.(3). SAFETY INDEX

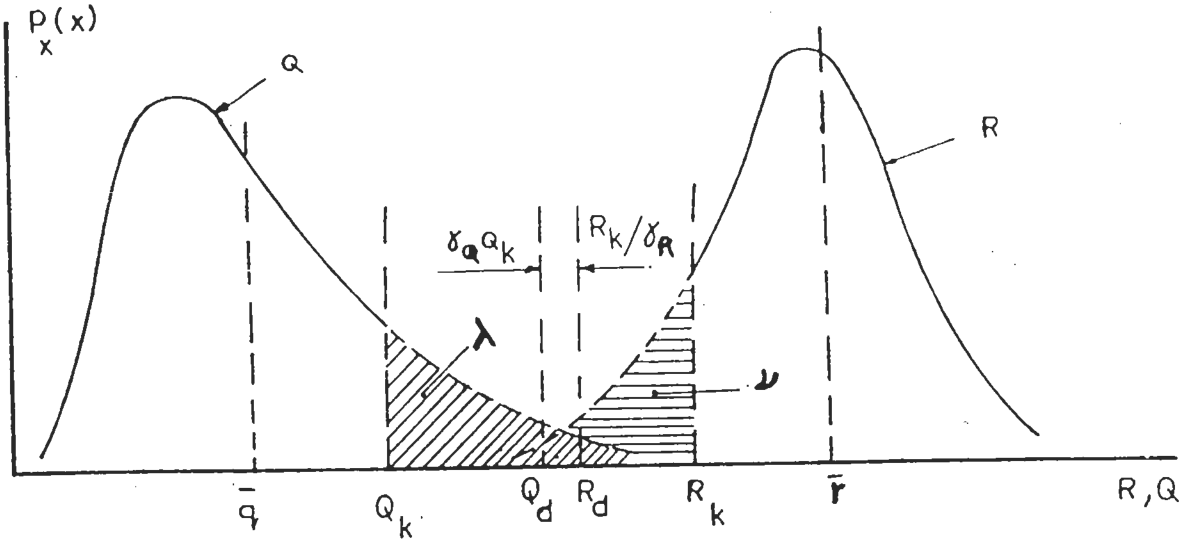
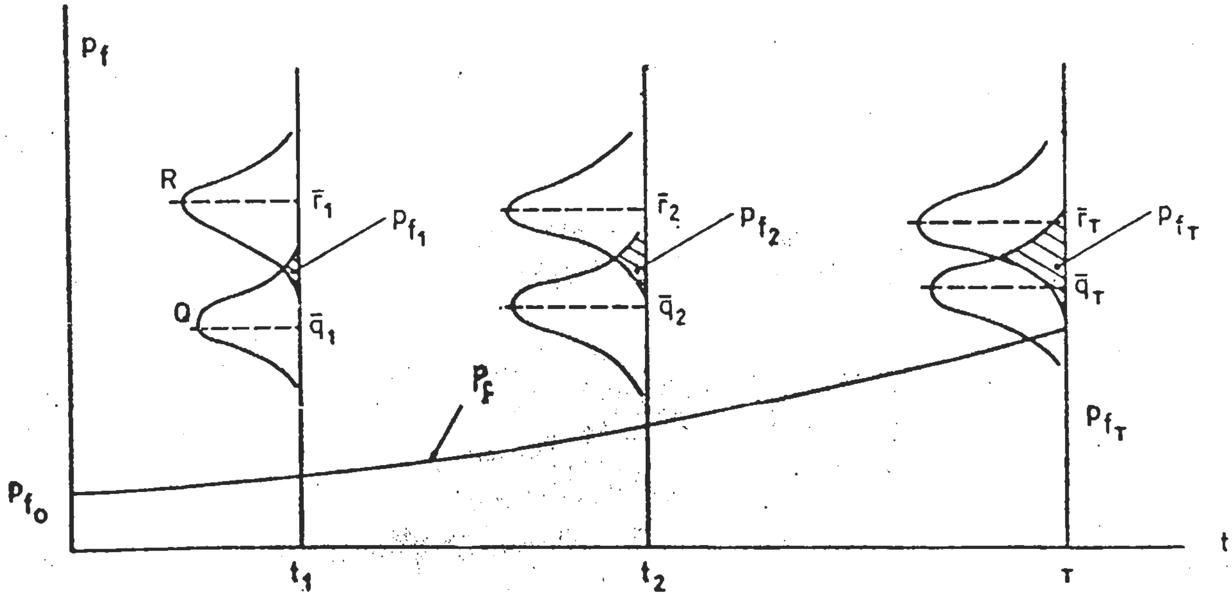



Fig.(4). Characteristic Values of R and Q




FIG(5).VARIATION OF $p_f$ WITH TIME

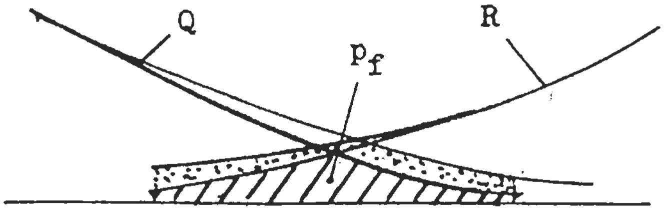



Fig.(6). TAIL SENSITIVITY PHENOMENON