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Appraisal - a Cyclical Process of Inspection and Calculation

Evaluation - un procédé alternatif d'inspection et de calcul

Bewertung - ein zyklischer Prozess der Inspektion und Berechnung

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SUMMARY

This paper describes the process of appraisal of existing structures with special emphasis on the refining of calculations by a conscious cyclical process of inspection and calculation.

RESUME

L'article décrit un procédé pour l'évaluation de structures existantes, mettant l'accent sur l'exactitude des calculs suite à un procédé alternatif conscieux d'inspection et de calcul.

ZUSAMMENFASSUNG

Der Artikel beschreibt das Vorgehen der Bewertung von bestehenden Bauten unter spezieller Betonung der Verfeinerung der Berechnungsmethoden durch einen bewussten zyklischen Prozess der Inspektion und Berechnung.

In 1742 Pope Benedict XlV, concerned with the state of the dome of St. Peters, requested three men, Le Seur, Jacquier and Boscowich to carry out a structural survey to determine the causes of distress and to devise remedial measures. The report, published the following year, was prefaced by an apology that said they had assessed it with theoretical mathematical reflection only because the building was so unique. Then followed a detailed survey of the dimensions and a discussion on possible explanations for the damage and named the yielding of the tie rings at the circumference as the cause. But the interesting part of this report was the second part because an attempt was made to calculate the horizontal thrust and to prove that the two tie rings built in at the time of erection were no longer able to carry this thrust.

The report caused a forore. One comment at the time stated: 'If it were possible to design and build St. Peter's dome without mathematics and especially without the new fangled mathematics of our time, it will also be possible to restore it without the aid of mathematicians and mathematics ... Michelangelo knew no mathematics and yet was able to build the dome ... Heaven forbid that the calculation is correct. For, in that case, not a minute would have passed before the entire structure would have collapsed.' Certainly the analysis contained some errors. But in spite of disagreements as to the causes of the damage most people were agreed on the measures to be taken, and in 1743 five additional rings were built in the cupola.

The importance of this event was that, contrary to tradition, the stability of a structure had not been based on empirical rules and opinion but on a detailed survey and mathematical analysis.

Today we are even more interested in developing the art of structural appraisal. We have a large stock of structures and buildings representing successive deposits of human imagination, which we are reluctant to discard for emotional or hard economic reasons. Urban renewal is a rapidly expanding exercise.

The art of appraisal of structures is different from design. In design the forces follow the choice of form and the analysis follows that. In appraisal the engineer is left face to face with an existing structure of definable qualities and must determine its condition and suitability of use. This is not an easy task.

The reasons for appraisal to assess the present condition may arise from change of ownership, change of use, deterioration in service, defects in the structure, future safety, accidental damage etc.

This requires consideration of the levels of safety appropriate to the further use of the construction, the assessment of loading, the evolution of methods for determining the strength of the structures, their components and constituent materials, and the derivation of suitable methods for calculating their composite behaviour. Requirements for remedial measures, restriction of use and monitoring performance may also form part of an appraisal procedure.

With this in mind the Institution of Structural Engineers in 1976 formed a working committee of experienced engineers to produce a guide to the appraisal of existing structures. This committee produced its report in 1980 and the authors of this paper are, in effect, representing the committee since one author was the Chairman and the other author one of the other two writers.

THE PROCESS

The process of appraisal is cyclical as shown in the flow charts (see Figs. 1, 2, 3 and 4). Information is collected and assessed. If the result shows that the structure is adequate the process can stop there. If inconclusive more information can be collected, assessed more thoroughly and so on. The action required should be taken in stages, each stage depending on the findings of the previous one.

Like all engineering activities, structural assessments are usually subject to cost and time limitations. The time spent on calculations should therefore be used as effectively as possible: There is no merit in an elaborate elastic analysis of a truss, if the strengths and stiffnesses of the joints are only imperfectly known. It would be far better to spend time studying the behaviour of the joints, using member forces from an approximate calculation.

STAGE 1

Gathering of Information

Fig. 1 illustrates the initial gathering of information. The first loop emphasises the need to obtain as much documentary evidence as possible: some effort at this stage may save a considerable amount of calculations and physical testing later. The other important operations are the site inspections: a) to make sure that the paper information is relevant to the actual building (and has not been superseded by a subsequent design alteration, lost in the meantime); b) to give the appraising engineer a first hand visual impression on how the structure performs in its present condition; this can be a very useful check on the validity of later calculations.

The Initial Assessment

Fig. 2 shows the processes which may be involved in ensuring that the structure is a stable configuration and not liable to progressive collapse in case of relatively minor accidental damage. It is important here, as elsewhere in appraising, to choose a mathematical model which not only is easily understood, in terms of stability, but also takes advantage of such physical features, which in ordinary design might be ignored but which, in the actual building, contribute significantly to stability (eg. infill brickwork panels in a framed structure).

The instructions following the question on collapse are reminders to the engineer not to leave an inherently dangerous structure just because it happens still to be standing, nor to be too easily satisfied with his first answer to the question of why it fell down.

Fig. 3 indicates the steps in the initial assessment of the strength of the structure.

The assessments of loads, forces and strengths of materials will at this stage usually be based on the available documents combined with the information from the in-situ survey. Tests on the actual materials will rarely be appropriate before the "simple check calculation"; they may however be called for in the course of the re-cycling loop under: "Re-assess Strengths ...".

"Simple check calculation" refers to the absence of assumptions and/or procedures beyond what is normally used in initial design. The "frame analysis" may at first be no more than reasonable estimates of support moments, but when "recycling" a proper analysis may be necessary. "Check satisfied" means that the calculation indicates (possibly by inference) that the recommendations of the relevant code of practice could be shown to be observed.

Attention is drawn to the repeated instruction: "Re-inspect Structure in-situ": This is a most essential, perhaps the most essential, step in the process, and without this cross-reference to reality, the entire appraisal can become invalid.

"Drastic Deficiency" may be assumed to be the case if the calculated overall load factor is 1.1, or less, on dead load alone.

If the results of the assessment at the end of this stage are unequivocal, one way or the other, there remains only to report the conclusions. If, however, the structure has been observed to carry most of its load with little or no sign of distress, but the calculations indicate an overall factor of safety greater than 1, but less than what is normally accepted, then it may be profitable to improve the basis for the calculation.

STAGE 2

Improving the Assumptions

The calculations, so far, have been based on conventional design assumptions. It is therefore worth examining the mathematical model for simplifications which may have led to over-conservative results of the calculations.

Another field for re-examination is the values used for loads and materials' properties: if they can be ascertained with less uncertainty than is the case for conventional pre-construction design calculations, then the same real factor of safety can be achieved with a lower calculated factor.

This may be most easily understood by considering the basic design equation in the partial factor format:

$$\gamma_s \times \text{load effects} = \frac{\text{structural resistance}}{\gamma_m \times \gamma_c}$$

where γ_s is a factor compensating for the uncertainties in predicting the effects of the loads, γ_m is a factor compensating for the uncertainties in predicting the resistance of the structure and γ_c is a modification factor compensating for differences in failure sequences and failure consequences. According to ISO 2394, each of these γ factors is made up of two or more sub-factors and their relation to appraisal of existing structures is discussed below.

I.S.O. 2394 DEFINITION	COMMENTS
γ_{s1} *takes account of the possibility of unfavourable deviation of the loads from the characteristic external loads, thus allowing for abnormal or unforseen actions*	The inherent variability of the live loads is clearly independent of whether the structure is existing or only at design stage. There is therefore usually no justification for reducing the γ_{s1} for live loads. Dead loads can often be ascertained with less uncertainty in an existing situation: thicknesses and densities of partitions and floor finishes can be measured, and so can actual structural dimensions. γ_{s1} can therefore be reduced for dead loads, provided adequate measurements and sampling are carried out.
γ_{s2} *takes account of the reduced probability that various loadings acting together will all be s simultaneously at their characteristic value.*	The probability of simultaneous occurence of loads of different origin should not change significantly from 'design stage' to 'as existing'. There is therefore usually no justification for varying γ_{s2}.

γ_{s3} is intended to allow for possible adverse modification of the loading effects due to incorrect design assumptions (introduction of simplified support conditions, hinges, neglect of thermal and other effects which are difficult to assess), constructional discrepancies such as dimensions of cross-section, deviation of columns from vertical and accidental eccentricities.

It is usually possible, albeit to a varying degree, to reduce the amount of approximation in the assumptions, when one is analysing a particular structure or element. 'Constructional discrepancies' can also sometimes be measured and included in the calculations of an existing structure.

Subject to the verisimilitude of the analytical model and adequate measurements of structural dimensions, γ_{s3} can therefore be reduced.

γ_{m1} is intended to cover the possible reductions in the strength of the materials in the structure as a whole as compared with the characteristic value deduced from the control test specimens

If the strength of the material in the actual structure is adequately tested, then the reason for introducing γ_{m1} has been eliminated. Usually, however, the testing regime, which complete elimination of γ_{m1} would require, is too onerous, but a reasonable amount of testing should nevertheless justify a worthwhile reduction of γ_{m1}.

γ_{m2} is intended to cover possible weakness of the structure arising from any cause other than the reduction in the strength of the materials allowed for in γ_{m1}, including manufacturing tolerances

This covers, among other things, the local variations, within the structure, of the strength of the material. When measurements include this, eg. when concrete core samples from the top and from the bottom of columns are tested, a reduction of γ_{m2} is justified.

This applies equally to design and to appraisal. Many design codes do not appear to vary their safety factors to take sufficient account of this but it should be possible to do so when assessing existing structures.

γ_{c1} is intended to take account of the nature of the structure and its behaviour: for example structures or parts of structures in which

In the case of brittle structures such as cast-iron columns and over-reinforced concrete beams, an increase in γ_{c1} will be called for.

partial or complete collapse can occur without warning, where redistribution of internal forces is not possible, or where failure of a single element can lead to overall collapse

γ_{c2} *is intended to take account of the seriousness of attaining a limit state from other points of view, for example economic consequences, danger to community etc.*

Here again, some existing design codes do not show any graduation, ie. the stipulated safety factors are the same for a 1m lintol as for a 15m beam over an assembly hall.

When appraising an existing structure one should distinguish between secondary members, failures of which will not cause progressive collapse, and primary members supporting other parts of the structure or secondary members which, if collapsing, might cause loss of life and limb.

The values for imposed loads are usually defined by Standards and Codes of Practice. All other values can, in the case of appraisal of an existing structure, be defined by observation and measurement. Defining at an appropriate level the values used for materials' properties is extremely important and the Institution of Structural Engineers' report provides a statement of the state of the art including a section on load testing.

Fig. 4 illustrates the improvement of the assumptions and reconsideration of partial safety factors.

It must however not be overlooked that extensive measurements, sampling and testing are time consuming and expensive and in some historical buildings they are nearly impossible to carry out without causing unacceptable damage to finishes.

The engineer should beware of initiating a surveying and testing exercise if he has doubts that they will lead to significant savings on strengthening works, because the end result could be that his client has to pay for both survey and remedial works.

The process of appraisal is cyclical because refinement of calculations is only justifiable if they are based on equally accurate factual information and facts may be expensive to collect.

On the other hand, there is no excuse for the intellectual laziness which condemns an old, good, building on the grounds that a conventional design calculation indicates non-compliance with a present-day code of practice.

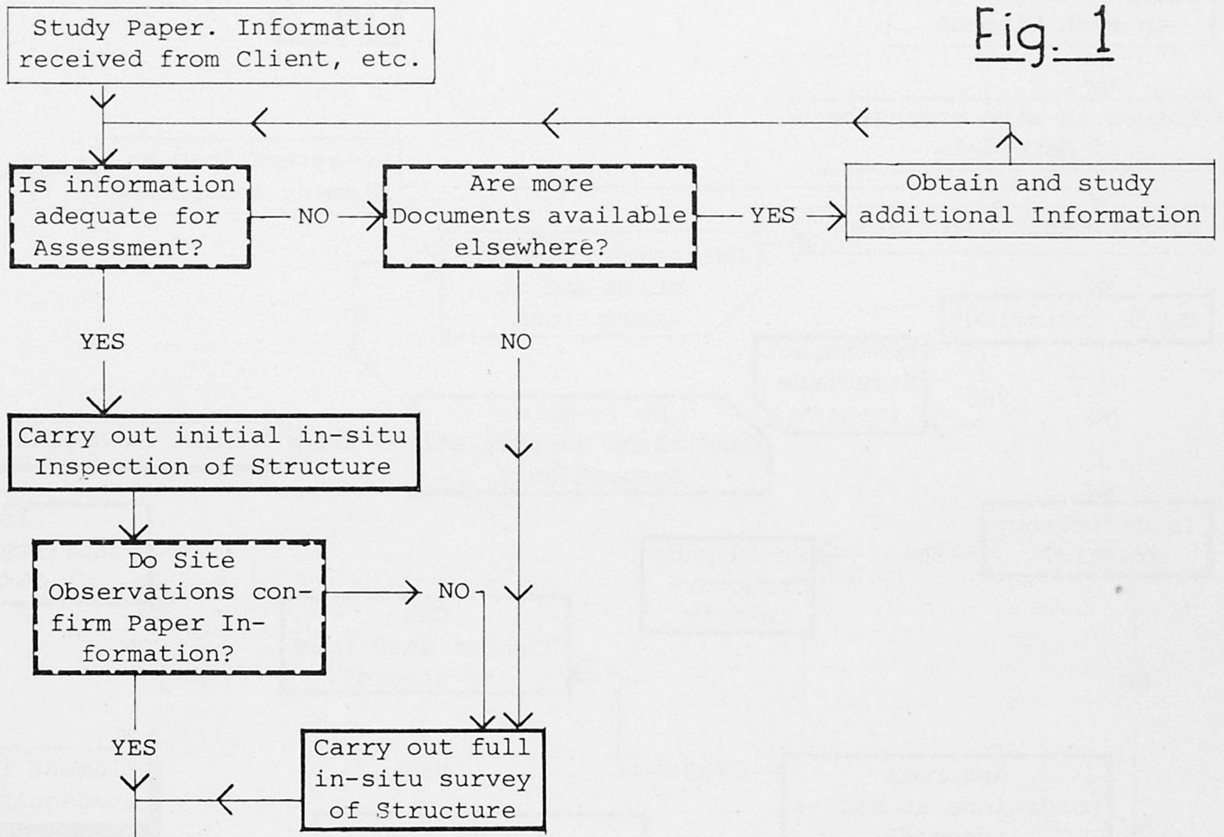
Study Paper. Information received from Client, etc.
Is information adequate for Assessment?
NO
Are more Documents available elsewhere?
YES
Obtain and study additional Information
YES
NO
Carry out initial in-situ Inspection of Structure
Do Site Observations confirm Paper Information?
NO
YES
Carry out full in-situ survey of Structure

Fig. 1

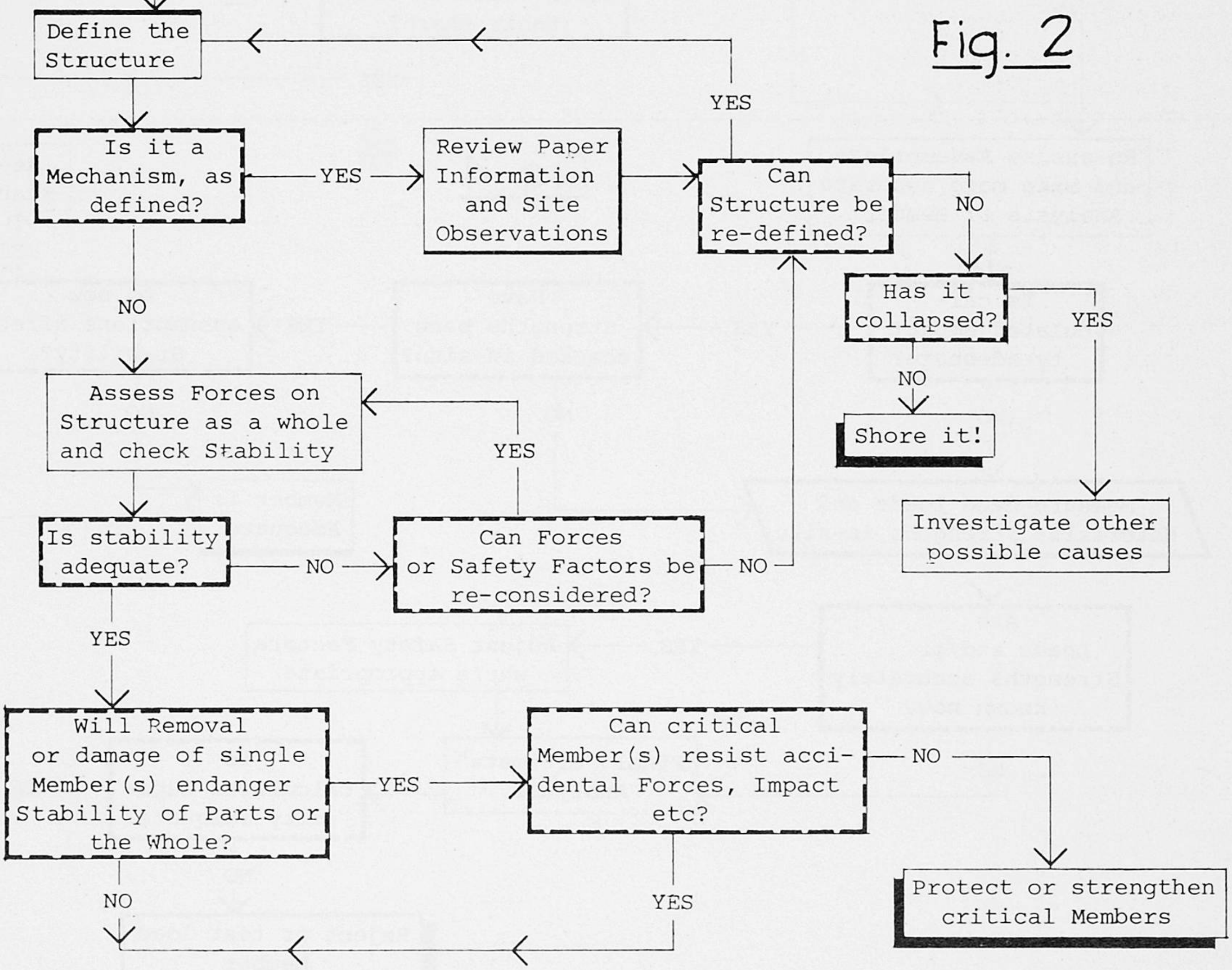
Define the Structure
YES
Is it a Mechanism, as defined?
YES
Review Paper Information and Site Observations
Can Structure be re-defined?
NO
Has it collapsed?
YES
NO
Shore it!
NO
Assess Forces on Structure as a whole and check Stability
YES
Investigate other possible causes
Is stability adequate?
NO
Can Forces or Safety Factors be re-considered?
NO
YES
Will Removal or damage of single Member(s) endanger Stability of Parts or the Whole?
YES
Can critical Member(s) resist accidental Forces, Impact etc?
NO
Protect or strengthen critical Members
NO
YES

Fig. 2

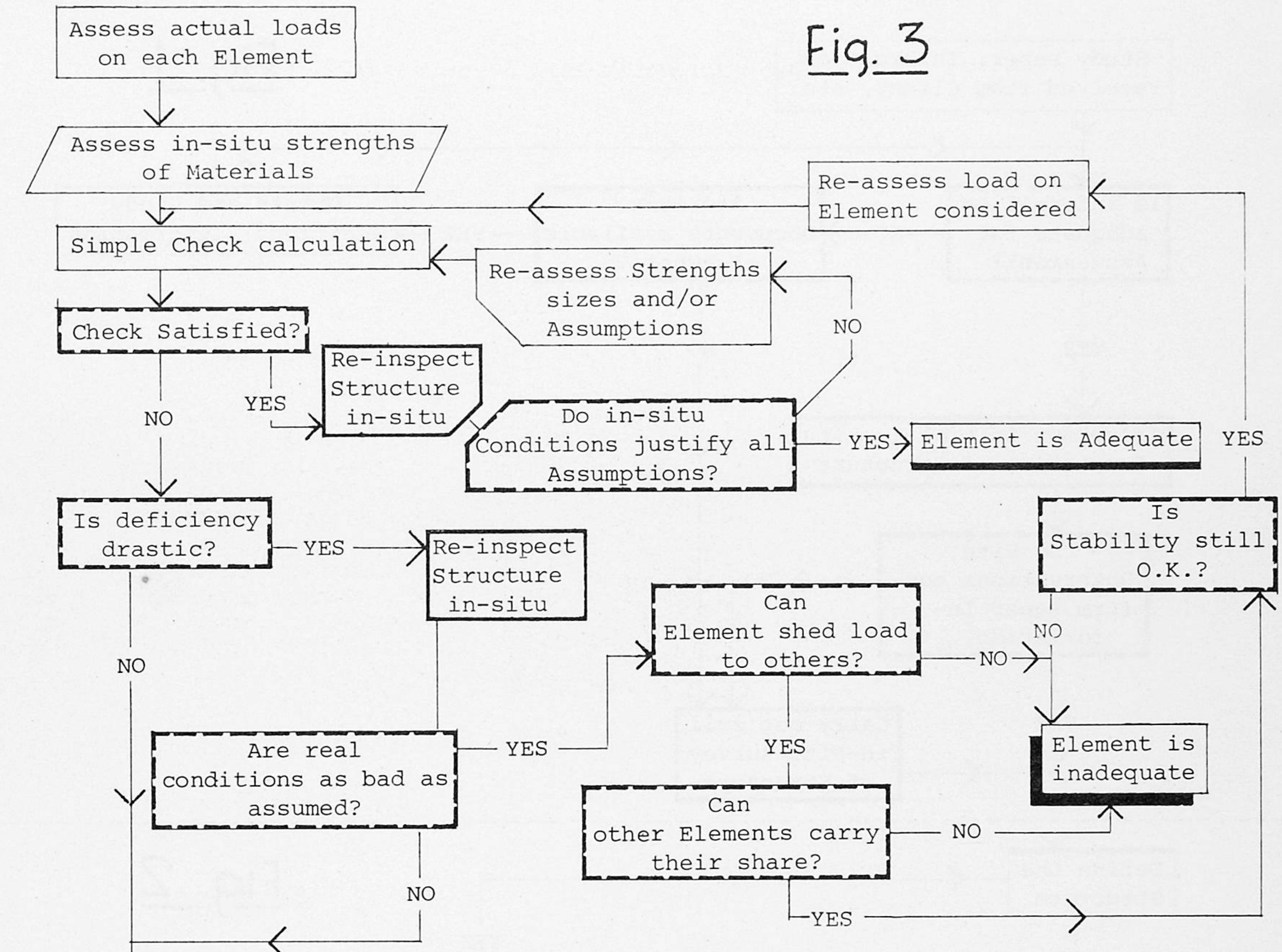
Assess actual loads on each Element
Assess in-situ strengths of Materials
Re-assess load on Element considered
Simple Check calculation
Re-assess Strengths sizes and/or Assumptions
Check Satisfied?
Re-inspect Structure in-situ
Do in-situ Conditions justify all Assumptions?
Element is Adequate
Is deficiency drastic?
Re-inspect Structure in-situ
Is Stability still O.K.?
Can Element shed load to others?
Are real conditions as bad as assumed?
Element is inadequate
Can other Elements carry their share?
YES
NO

Fig. 3

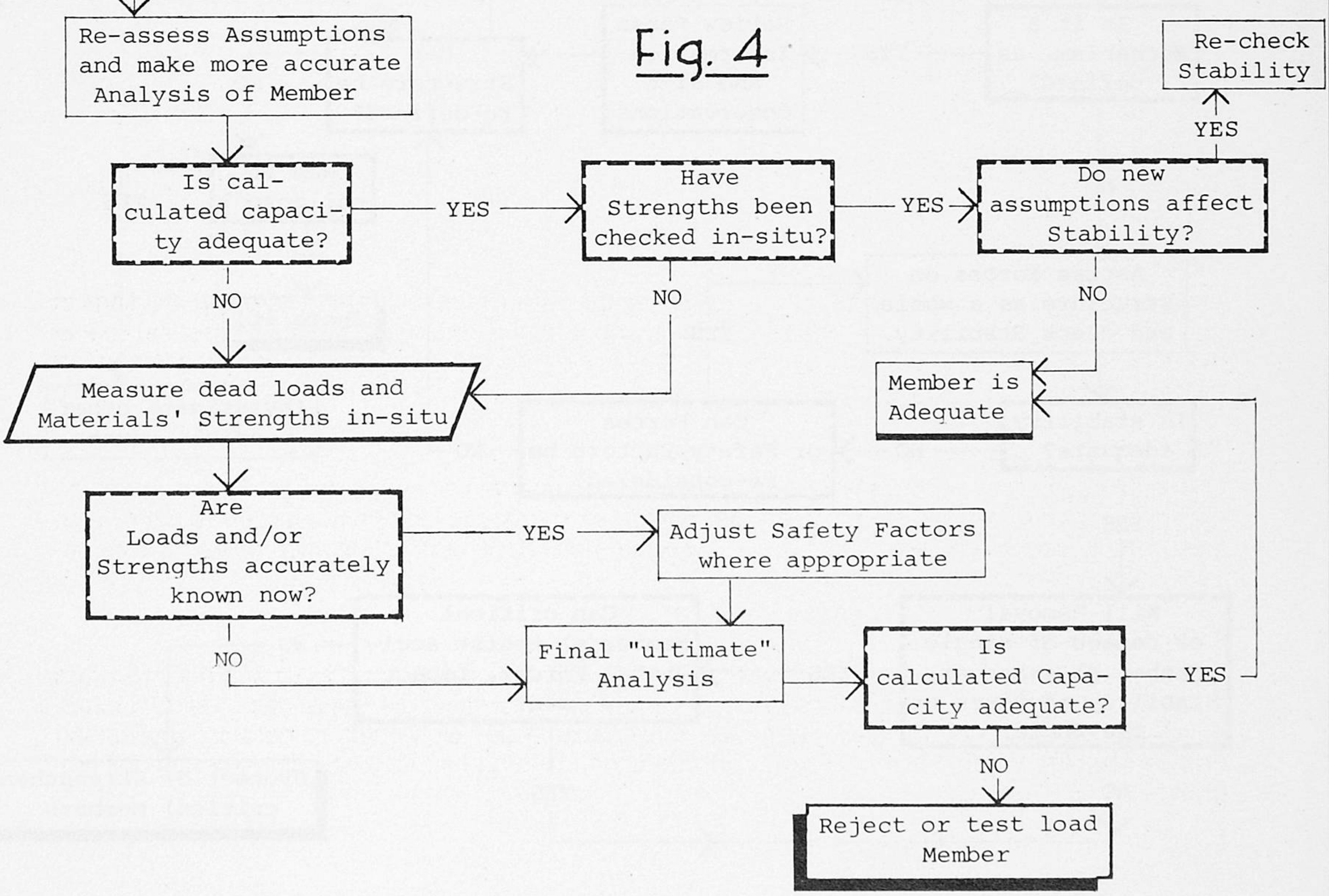
Re-assess Assumptions and make more accurate Analysis of Member
Re-check Stability
Is calculated capacity adequate?
Have Strengths been checked in-situ?
Do new assumptions affect Stability?
Measure dead loads and Materials' Strengths in-situ
Member is Adequate
Are Loads and/or Strengths accurately known now?
Adjust Safety Factors where appropriate
Final "ultimate" Analysis
Is calculated Capacity adequate?
Reject or test load Member
YES
NO

Fig. 4