SOME LESSONS DRAWN FROM TESTS WITH STEEL STRUCTURES*

O. Halász and M. Iványi

Department of Steel Stuctures, Technical University, H-1521 Budapest

Received September 21, 1984

Abstract

The concept of limit states requires the analysis of structures at different load levels. As demonstrated by the example of full-scale tests with simple frames, the corresponding traditional methods of analysis give usually reliable results at lower (working) load levels, but methods of predicting ultimate load include a series of uncertainties and require experimental verification.

Introduction

The increasingly powerful experimental and computational tools of structural design require well-defined design philosophy. As its basis seemingly the concept of limit states [1] is accepted in many countries, requiring the check of the (small enough) risk that the given structure be brought in its ultimate state (failure) and the (somewhat bigger) risk of the occurrence of phenomena restricting its regular use (serviceability). All this (excluding now brittle fracture and fatigue) necessitates the analysis of structural response at a broad range of load levels: from working loads up to exceptionally high ones.

As pointed out in the literature (e.g. in Gvozdev's excellent book [2]) in different periods of developing engineering practice different importance was attributed to the two classes of limit states. In the earliest periods (e.g. in the works of Coulomb) — possibly inspired by the experience of collapsing vaults and breaking down earthworks — interest was focussed on the ultimate state and accordingly the applied methods of analysis could describe the last phase of structural response only (as still in use, e.g., in some branches of soil mechanics).

A second period can be connected to the activity of the brilliant French scientist Navier, who seems to have been more interested in the second class of limit states. Quoting the preface of his book [3] of enormous influence on engineering practice: "Knowing cohesion ultimate load to be carried by a body can be determined. For the structural engineer, however, this isn't sufficient, the question being not to know the force big enough to cause breakdown of the

---

* This paper was a contribution to a book commemorating the 70th birthday of Prof. Ch. Massonnet, one of the most outstanding scientists in the field of structural sciences. ("Verba volant, scripta manent", Liège, 1984.)

body, but rather the load to be carried by the structure without causing in it changes progressing with time." This viewpoint originated the concept of allowable stresses and the corresponding methods of analysis: the "accurate" and simplified methods based on the theory of elasticity which were good enough to describe structural response at relatively low (working) load levels.

Let us associate a subsequent period with the work of the Hungarian scientist Kazinczy, who is regarded as the initiator of plastic design of steel structures. In his early — and because of its language hardly accessible — paper [4] on his tests with fixed-end beams he confesses: " . . . In case of statically redundant steel structures exhibiting different kind of response to higher loads than to lower ones . . . the allowable stress is meaningless, giving no information about margin of safety whatsoever." This indicates that main interest was shifting again towards the first class of limit states, towards failure.

Accordingly research was directed to complete the methods of analysis with new ones (based among others on the theory of plasticity) describing structural behaviour in the vicinity of and at the peak load and often in post-failure phase as well.

Thus recent concept of limit states can be regarded as a balanced synthesis of the previous design philosophies.

Difficulties in Predicting Failure

In contrast to the expectation of the initiators of plastic design the analysis of structural response in the vicinity of peak load proved to be extremely complicated, due not only (and even not mainly) to inelastic behaviour, but to the fact, that in the vicinity of peak load

- — change in geometry (geometrical non-linearity) gains in importance among others because of magnifying the effect of initial geometrical imperfections (often negligible at lower load levels),
- — residual stresses (remaining latent at lower loads) interact with growing active stresses resulting in premature plastic zones, and last but not least
- — usual and widely accepted tools of analysis — as beam theory based on the Bernoulli-Navier theorem; small deflection theory of plates etc. — restricting the actual degree of freedom of the structure cannot describe exactly enough its real response at failure.

These difficulties can be overcome in case of simple structural elements (separated compression members, parts of plate girders, etc.) by using more refined (e.g. finite element) methods, allowing degrees of freedom (e.g. distortion of cross sections) excluded in traditional analysis, etc., or even in case of

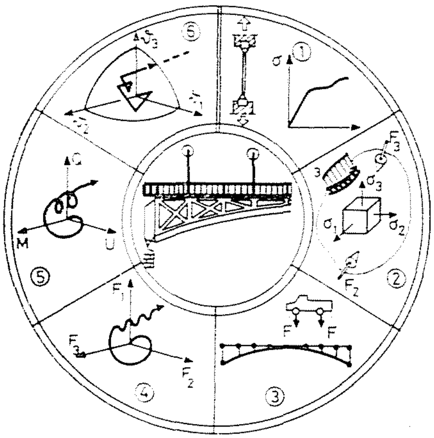

Fig. 1

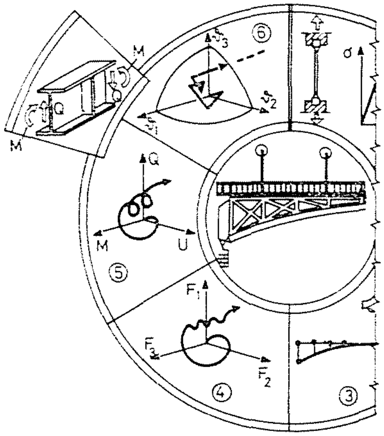

Fig. 2

statically non-redundant structures, where the above indicated complex behaviour is usually confined to a limited section of the whole structure. Then the procedure can be illustrated by Figs 1 and 2.

Figure 1 indicates the classical way: (1) finding the appropriate constitutive law; (2) using basic notions and equations of mechanics of continua; (3) establishing a mathematically treatable simplified model of the structure using thus, e.g., simple beam theory; (4) describing load history by means of a load-trajectory in a load-space; (5) computing the corresponding change of primary parameters (trajectory of load-actions, stresses, deflections) describing structural response; (6) selecting out of them the so-called quality parameters ϑ_i [5] (e.g. maximum moments or stresses) playing decisive role in judging the onset

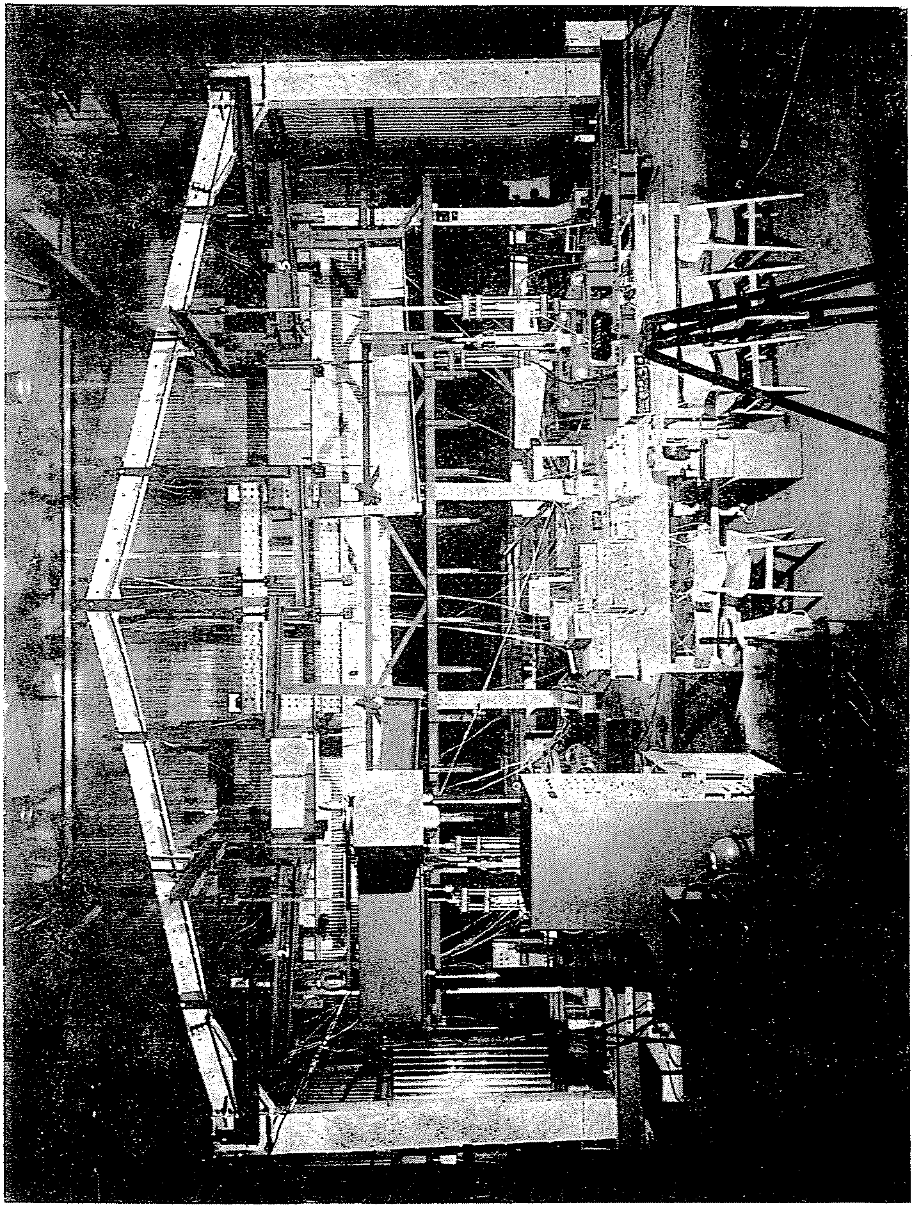

Fig. 3

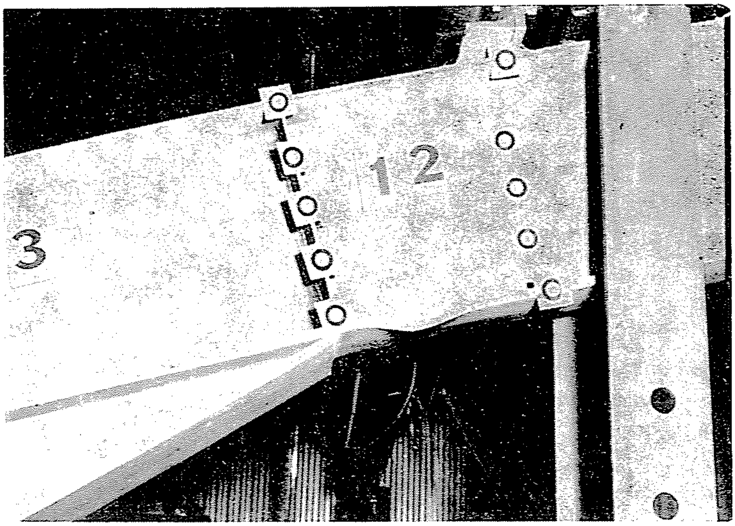

Fig. 4

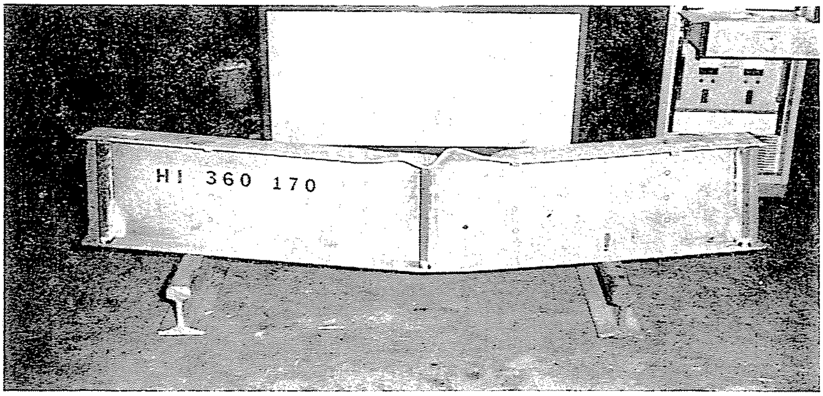

Fig. 5

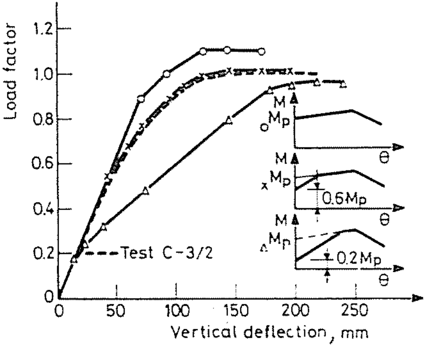

Fig. 6

of limit states; which again can be defined by the intersection of the trajectory of quality parameters with a given limit surface.

If the simplified model is not elaborate enough to reflect real structural behaviour, a secondary, more detailed local model is inserted (see Fig. 2) to depict the mostly critical part of the structure, by which more realistic quality parameters (and limit surface) can be deduced from the already known primary parameters.

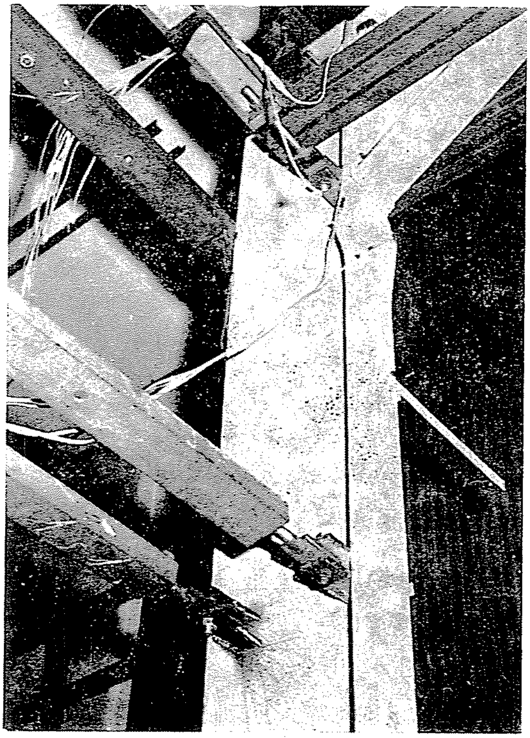

Fig. 7

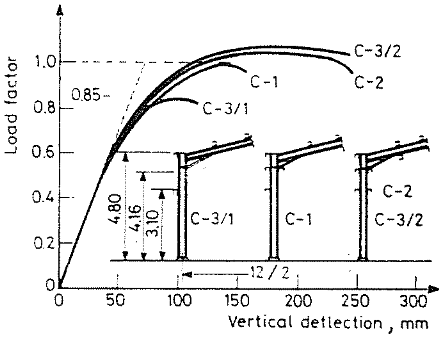

Fig. 8

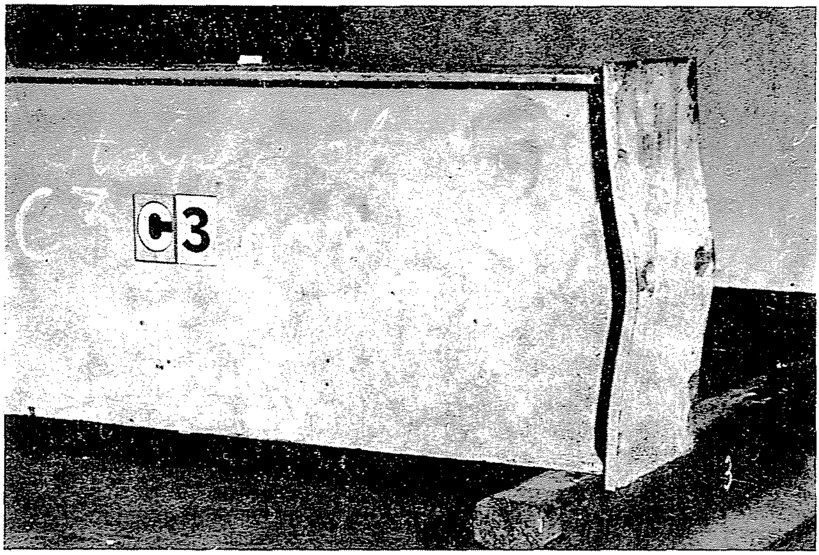

Fig. 9

Because of the interaction of local and global behaviour this pattern cannot be followed in case of hyperstatic structures, as the additional information gained by the secondary, local model is to be fed back to the computation of primary parameters as well. For this purpose, if — as very often — the secondary model can be analysed by numerical methods or only experimentally, the results have either be re-interpreted to gain mathematically treatable, simple enough rules, or the secondary model has to be simplified to furnish digestible results. In both cases the validity or accuracy has to be proved by (usually very expensive) failure tests with whole structures. The same applies for directly non or hardly measurable quantities, as residual stresses.

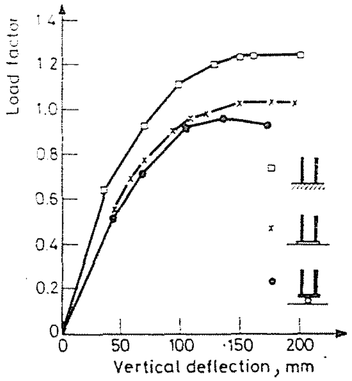

Fig. 10

Illustrative Example

Full-scale failure test with simple frames built up of relatively thin-walled I-shapes is shown in Fig. 3. The main problem in describing its response was a realistic representation of the local behaviour of "plastic hinges" (Fig. 4) including the effect of residual stresses, strain hardening and local buckling, which often starts before the collapse of the whole structure.

The results gained by separate tests (Fig. 5) and corresponding involved [6] analyses are re-interpreted by three different moment-rotation diagrams (Fig. 6): the first one neglecting, the second and third ones supposing different values of residual stresses. These relations are simple enough to be included in the global second-order analysis of the frame and the three corresponding load-deflection diagrams are indicated in Fig. 6 as well; the one in the middle proved to be only in good coincidence with full-scale test results.

It seems worth-while to draw the attention to the fact also, that minor differences in structural details — having no influence at lower load levels — may have decisive role at failure.

Figures 7 and 8 indicate that lateral supports equally spaced but differently connected to the compression flange result in different limit loads and differently shaped load-deflection diagrams.

Similar effect has to be attributed to the actual behaviour and moment-carrying capacity of the column base (Figs 9 and 10).

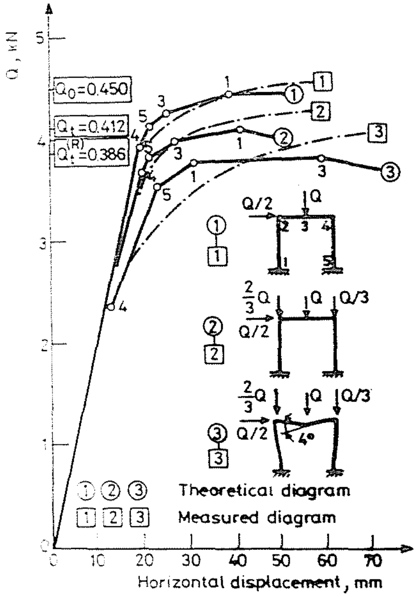

Fig. 11

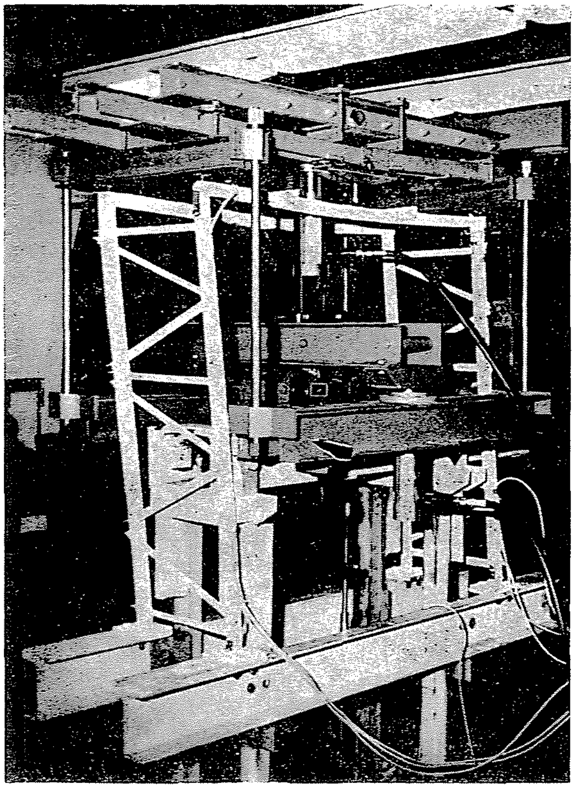

Fig. 12

Finally test results and corresponding analyses [7] (Figs 11 and 12) indicate, that in case of high axial loads residual moments originated by forced elimination of small lacks-of-fit at connections may considerably decrease limit load.

Conclusions

While traditional ways of structural analysis seem to furnish reliable enough and general methods to follow structural response well below failure, methods to predict failure load itself include a series of uncertainties, are forced to use approximate models and procedures bound to special structures, and need regular experimental checks. This fact has to be counted with in judging the role of different limit states and the required level of risk predicted by computation.

References

1. MASSONNET, Ch.—MAQOI, R.: Recent Progress in the Field of Structural Stability of Steal Structures. IABSE Periodica *2/1978*, 1 (1978).
2. GVOZDEV, A. A.: Ultimate Load Analysis of Structures. (in Russian). Gosstroizdat, Moscow, 1949.
3. NAVIER, L. H.: Résumé des leçons données à l'école des ponts-et-chaussées. Paris, 1826.
4. KAZINCZY, G.: Experiments with Fixed-end Beams. (in Hungarian). Betonszemle, *2*, 68 (1914).
5. BOLOTIN, V. V.: Reliability Theory and Structural Stability. University of Waterloo, Study No. 6. 385 (1952).
6. HALÁSZ, O.—IVÁNYI, M.—SZATMÁRI, I.: Experiments with Plates in the Postbuckling Range (in Hungarian). Műszaki Tudomány, *64*, 101 (1981).
7. HALÁSZ, O.: Effect of Initial Imperfections on the Elastic-plastic Failure Load of Simple Frames. Int. Coll. on Stability of Steel Structures, Liége, 1977. pp. 13—22.

Prof. Dr. Ottó HALÁSZ
Prof. Dr. Miklós IVÁNYI } H-1521 Budapest