Calculation of Strength of Safety Frames for Tractors

By KYŌSHIRŌ MIURA and FUMITAKE ISHIKAWA

Safety Engineering Laboratory, Institute of Agricultural Machinery

As the usefulness of safety frame or safety cab in preventing fatal accidents by the overturning of agricultural tractors was recognized from the experiences in Sweden and other countries since late 1950s, European countries made it an obligation to equip the approved safety frames to new tractors already in the early half of 1970s, and the later half of 1970s enterd into a stage that even used tractors are obliged to be equipped with safety frames. Technical agreement which gives the basis for these legal regulations was obtained at an international level that the strength of safety frame/cab can be assured by the 'OECD Standard Code for the Official Testing of Safety Cabs and Frames Mounted on Agricultural Tractors'. An important aspect of that Code is the impact test in which the frame offered is striken by a pendulum (a weight of 2000 kg suspended from a pivot point about 6 m above the floor) with the impact according to the weight of tractor.

Since 1969, the authors have carried out a series of study on the safety frame by the use of such apparatus. The main objective of the study was to establish a method by which deflection of frame or behavior of deflection caused by the impact test can be calculated in advance, with an aim of saving labor and cost at the designing stage, because the method of Test Code is essentially a destructive test. The study was completed in 1974: by this time the effectiveness of safety frame has gradually been appreciated by many peoples concerned also in Japan, and as a result the National Test of Safety Frame has come to be initiated since 1975.

Method of calculation developed by the authors will be described briefly in the present paper. Great problems which came out in the course of the study were (1) that a large deflection of the safety frame is allowable as far as the tractor operator can be protected, and (2) that the load by the pendulum is impulsive. These problems were solved by integrating the property of mild steel under such conditions into the algorithm. In the order of the procedure taken to solve them, the problem of plastic deflection will be taken up at first, followed by the problem of impact and then their results will be combined.

Elastic-plastic structural analysis under static loading

In the case of the safety frame, the permanent deflection after the removal of a working load is allowed within a certain limit. Actually the occurrence of permanent deflection serves to absorb a large proportion of the impact energy and to reduce the load on the tractor mounting points. To bring the property of materials beyond the elastic limit into structural analysis for such a case as above, it was considered that the principle of 'plastic design' which is becoming to be used practically in the field of construction could best be introduced.

The concept of plastic design can be summarized as follows: contrary to the elastic design which deals with the loading limit until the extreme fibres of the section yields, the plastic design deals with the loading limit until the whole section comes to yield. The point of a structural member, where the whole section yielded, rotates just like a hinge, holding a constant resisting moment, and it is called as plastic hinge.

The authors carried out static loading tests with model frames, observed sequential occurrence of plastic hinges, and obtained load-deflection curves. On the other hand, the elastic analysis by means of matrix method was improved by incorporating the concept of plastic hinge, and computer programme of elastic-plastic analysis was developed (Fig. 1). Load-deflection curves calculated by the computer were compared with the results of static loading tests. A fairy good coincidence was confirmed (Fig. 2).

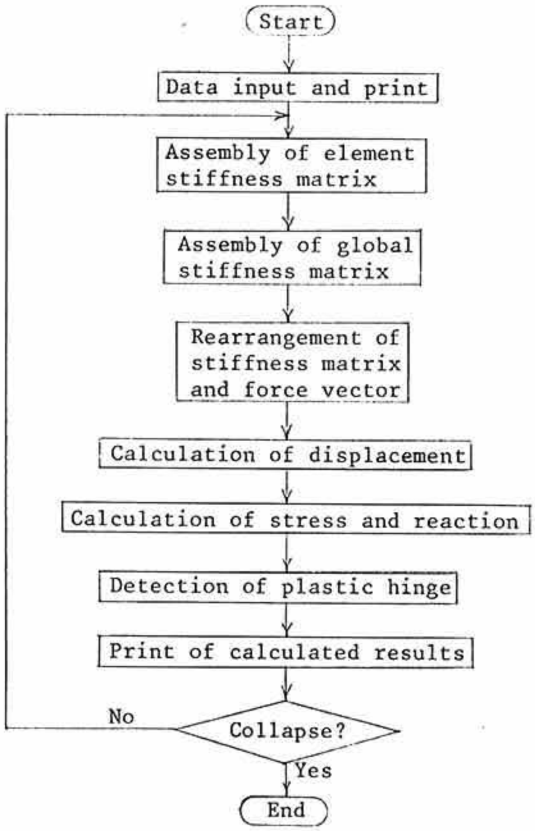

Fig. 1. Flowchart of elastic-plastic analysis

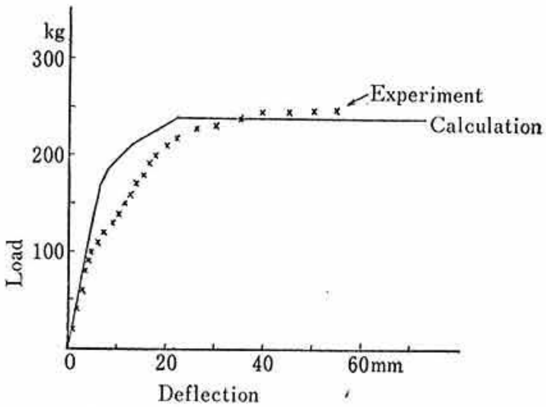

Fig. 2. Load-deflection curve of model frame

Response of structure under dynamic loading conditions

It is well known that the yield strength is increased considerably when dynamic loading is given to mild steel. This property is summarized by many researches as given in Fig. 3, which shows a linear relationship between the ratio (σ_d/σ_s) of dynamic yield stress (σ_d) to static yield stress (σ_s), as expressed by logarithmic scale, and the time required to yield, expressed by logarithmic scale. Rawlings (1964)[1] and Watson (1967)[2] reported that

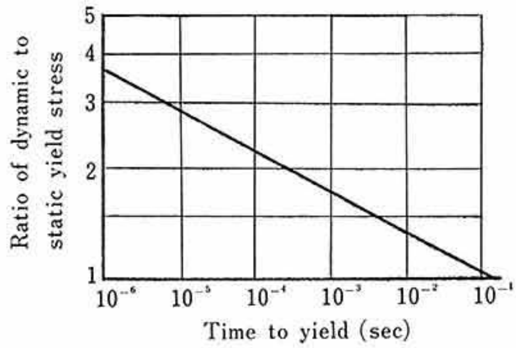

Fig. 3. Relationship of (dynamic yield stress/ static yield stress) with time to yield (from Rowlings, The dynamic behaviour of mild steel in pure flexture. 1963)

this property can be applied to structures. Especially Watson found that the value of σ_d/σ_s was 1.3–1.5 in the impact tests of safety frame that were carried out to formulate the Tractor Safety Frame Regulations in New Zealand.

Calculations of dynamic yield stress adopted by us are as follows:

1) Static yield stress was determined by tensile tests,
2) Displacement of loading point at the time of impact tests was recorded on an oscillograph through a displacement gage, and at the same time the behavior of the whole safety frame was recorded on 8 mm cine films,
3) From these records, displacement of pendulum and loading point, and velocity of pendulum were obtained, and the power (P_d) given to the safety frame was calculated,
4) σ_d/σ_s was obtained from the time to yield, and
5) After confirming that the ratio ($P_d/P_s = \sigma_d/\sigma_s$) of collapse load ($P_s$), obtained by calculations or static loading tests, to P_d is close to the σ_d/σ_s obtained in the above 4), the final value of σ_d/σ_s was determined.

Table 1 shows results of impact tests of safety frame models produced for experimental purpose. For test Nos. 21, 22, and 31, the safety frames were mounted to a stand as shown in Plate 1 in order to avoid the absorption of a part of impact energy by deflection of tires. The table indicates that σ_d/σ_s is 1.3–1.4. At the stage of designing, it would be appropriate to adopt the value as 1.3.

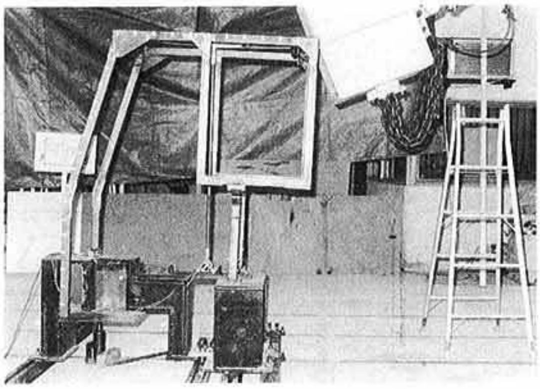

Plate 1. The impact test of safety frame, type 733, mounted on a stand

Comparison between calculated and experimentally determined values

Maximum and residual deflection under impulsive loading were calculated by means of elastic-plastic analysis method above mentioned, for safety frame models shown in Table 1. The calculation gave similar results to obtained in impact tests. Fig. 4 illustrates load-deflection curves obtained by calculations or impact tests in experiment Nos. 21 and 31. As to the energy absorption by deflection, it was found that almost 100% of impact energy with 5% error was absorbed when the frame was mounted to a stand, whereas with tractor-mounted frames energy absorption differed

Table 1. Results of safety frame impact tests

Test No.	Type	Main materaial used for construction	Mounted on	Direction of blow	Impact energy (A) kg·m	Calculated deflection (mm) Max.	Calculated deflection (mm) Res.	Actual deflection (mm) Max.	Actual deflection (mm) Res.	Energy absorbed by frame (B) kg·m	B/A (%)	σ_d/σ_s
21	732A	A	Stand	Rear	293.5	221	164	219	163	278.8	95.5	1.31
22	732	A	Stand	Side	556.6	485	398	360	278	567.7	102.0	1.32
23	732	A	Tractor	Rear	293.5	221	164	231	153	275.6	93.9	1.32
24	732	A	Tractor	Side	556.6	485	398	255	146	302.2	53.4	1.36
31	733	B	Stand	Side	556.6	327	230	328	217	538.2	96.7	1.30

A : steel pipe, JIS G 3101 STK41 48.6ϕ t2.4　　B : square steel pipe, JIS G 3101 STKR41 50×50×2.3

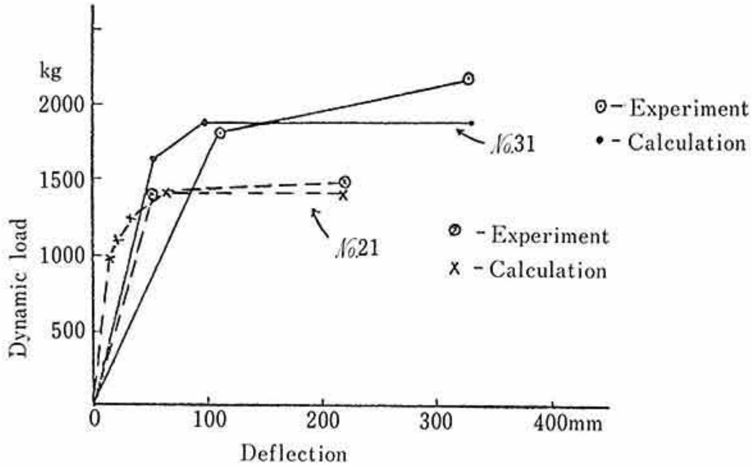

Fig. 4. Dynamic load-deflection curve of full size frames on test stand

with direction of impact: 80–90% of energy was absorbed in case of rear blow and front blow, and 50% in case of side blow.

Design criteria for safety frame

Based on the above results, the authors formulated the design criteria for safety frame as given in Fig. 5. Some explanations will be given on major aspects.

1. General structure: Structure and shape should meet the general requirements of the safety frame. As the basic rule, four posts type safety frame made of mild steel should be used. Assembling and connection of main parts should be done by welding as an essential prerequisite.
2. Materials: Mild steel SS41 prescribed by JIS G3101 'Rolled Steel for General Structure' or SM41 prescribed by JIS G3106 'Rolled Steel for Welded Structure' should be used. Static yield stress to be used for designing should be 24 kg/mm^2 in case of normal stress and 13.8 kg/mm^2 in case of shearing stress. It is desirable to use steel pipe or square steel pipe for the section.
3. Impact energy: As the weight of safety frame is given in the above 2, weight of tractor is derived from it, and impact energy (E_i) at each impact direction is calculated.
4. Structural analysis: Following the flow in Fig. 1, structural analysis is made to get static load-deflection curves. Multiplying by 1.3 (σ_d/σ_s), dynamic load-deflection curves are derived.
5. Allowable deflection (δ_a): In relation to the zone of clearance, maximum allowable deflection (δ_a) at a loading point is determined.
6. Energy absorption: Absorbed energy (E_a) at δ_a is determined by the dynamic load-deflection curves.
7. $\alpha E_i \leqq E_a$ (α=0.8 for rear and front blow, α=0.5 for side blow): Whether more than 80% (50%) of the impact energy is absorbed by the deflection of safety frame or not is to be examined.
8. Selection of part's section: If $\alpha E_i > E_a$, select stronger material.

10. Strength of tractor mounting points: Strength of tractor mounting point is examined. If the housing of tractor is not strong enough, it is liable to be broken.

12. Impact and crushing test: Tests based on impact and crushing tests prescribed in various countries have to be carried

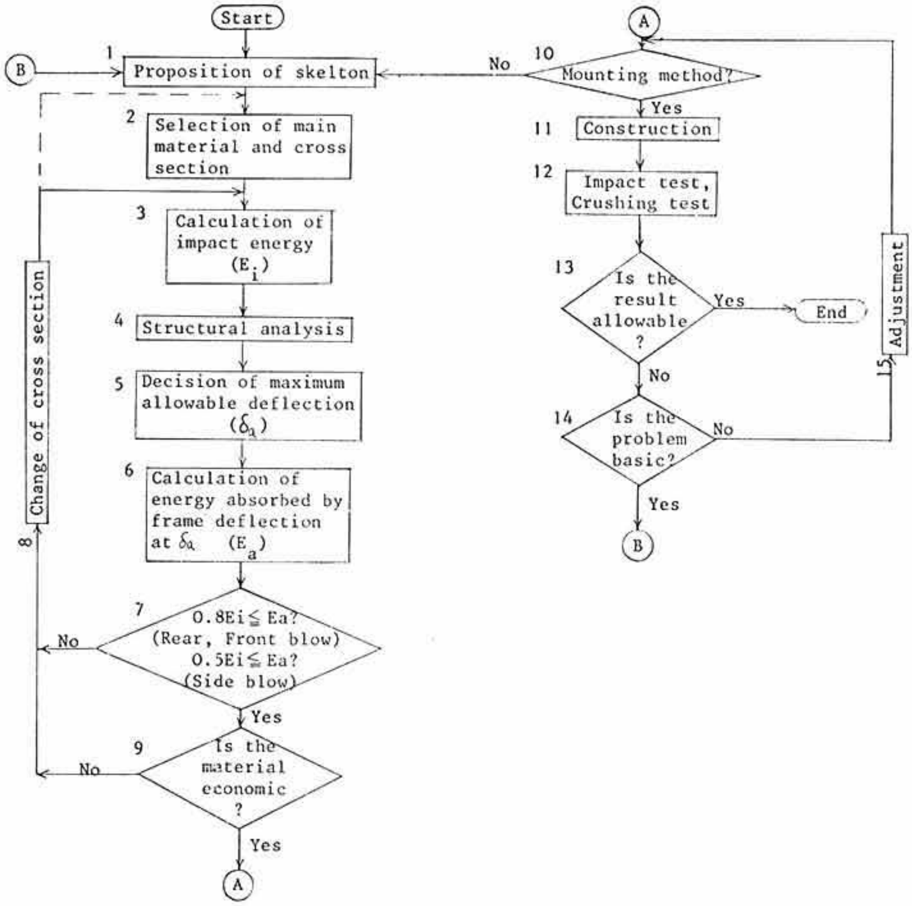

Fig. 5. Flowchart of design criteria for safety frame

out to check whether the requirements for safety frame is met or not.

14. Correction of structure: When results of the impact and crushing tests are not allowable, a decision is made whether overall revision is rather easier for technical point of view, or simple reinforcement is enough.

References

1) Rawlings, B.: Impact test on model steel frames. *Proc. Inst. Civil Eng.*, 29(4) 389–414 (1964).

2) Watson, E. M.: The structural testing of tractor safety frames. New Zealand Agricultural Engineering Institute Research Publication R/1 (1967).