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BETREFFENDE:

Measurements of dynamic crack opening displacements of notched steel test specimens under impact loading, according to the "Niblink" test procedure.

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CONTENTS:

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By S. Kubera. *

1. Introduction.

The Crack Opening Displacement (COD) concept is accepted in the past few years as useful for analyzing fracture toughness of steel structures in service conditions, as well as a criterion for the initiation of brittle fracture /1/. The Crack Opening Displacement is defined as the relative movement of the two crack surfaces at the crack tip, without increase in length of the crack in consequence of plastic flow by the loading.

In tests to determine the material properties, the critical value of COD at fracture or instability point is estimated by tension or bending /2/ on appropriate for this aim notched specimens. The maximum value of COD by loading can be plotted autographically, applying special clip gauges and the residual value after unloading can be measured with special dial gauges /3, 4/.

Recently /7/ electrostatic capacitance methods of COD measurements were used to determine brittle initiation characteristics of deep notch test specimens. All these methods are appropriate to measure COD values in static or quasi-static conditions of loading, or after unloading the specimen. Only few cases /5, 6/ regard the attempt of the measurement of the dynamic COD value by impact tests, using the method of photographical records.

For the investigations, conducted in the Ship Structures Laboratory (SSL) of the Delft University of Technology in 1970/71 , regarding the physical meaning of the COD residual value by multi-blow impact bending according to the NIBLINK /4/ test procedure, resistance strain gauges instrumentation with special set of apparatus was employed, enabling the measurement and recording of the dynamic values of the COD at the moment of the blow. This method may be useful also in other investigations and it gave impulse for preparing this paper.

2. Principle scheme of measurement.

The impact loading of the specimen caused by a drop-weight, satisfied the conditions required by the NIBLINK tests. Energy of blow En = Q.H; the constant drop-weight (Q) depended on the drop-weight height (H). The heights were increased stepwise for the consecutive blows, the speed of loading increased with the square root of the height.

The energy of blow was transmitted to the test-specimen through the bridge-part on which strain gauges were attached for measuring the impact force (F). (Fig. 1).

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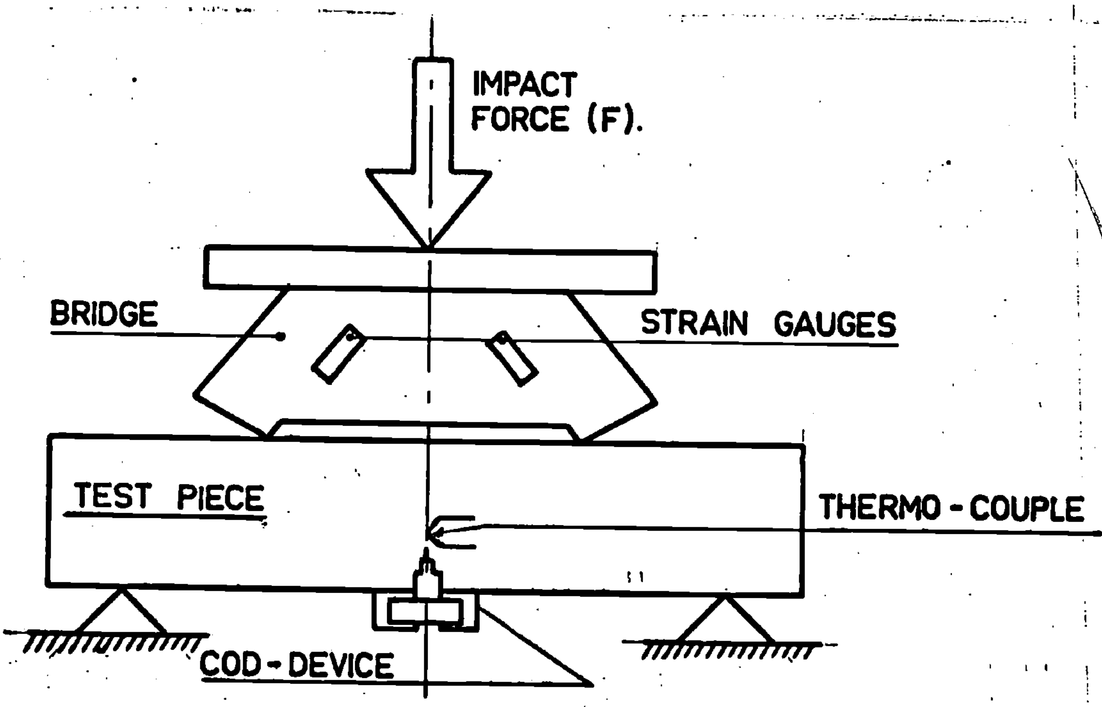

FIG. 1. Loading scheme of the specimen.

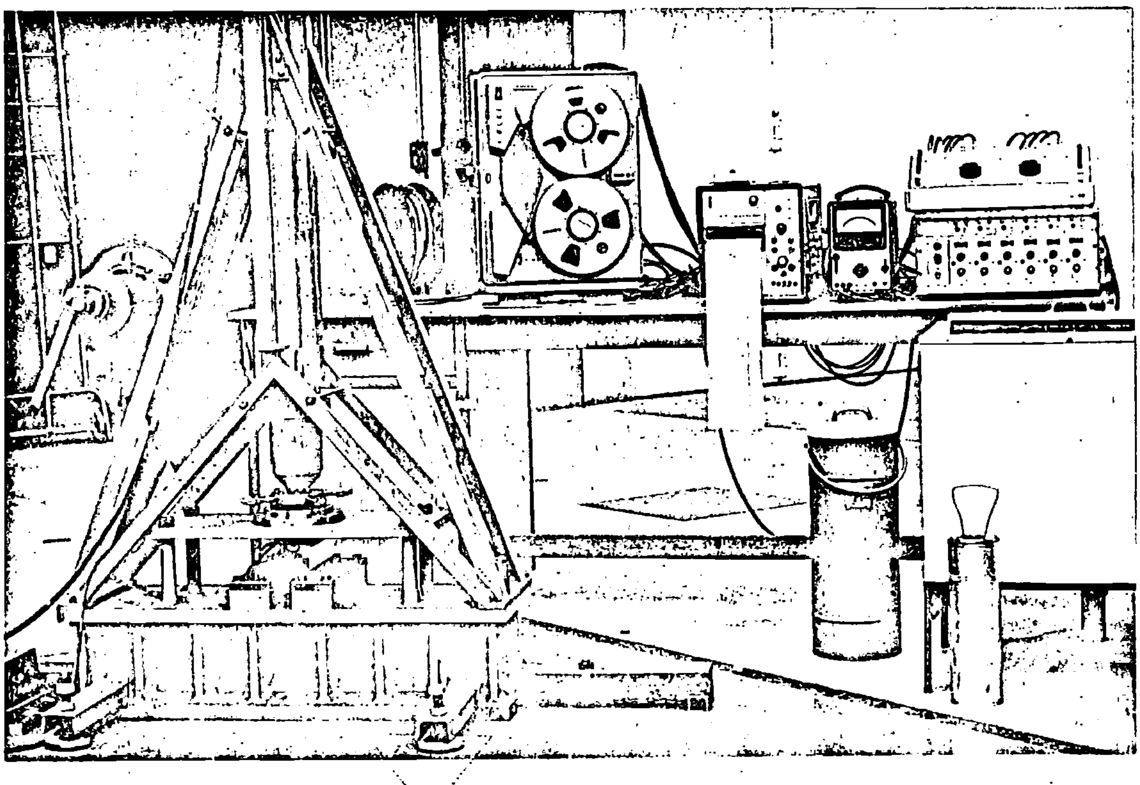

FIG. 2. General view of drop-weigt test equipment.

Fig 1

The special COD-measuring device was attached directly to the test-piece in the region of the notch slit. For temperature check in tests at lower temperatures, thermocouples were fixed to the test-specimens in the vicinity of the notch.

The drop-weight test equipment and the whole set of apparatus is shown in fig. 2.

Fig. 2.

The COD-value by the impact was registered simultaneously with the impact force on the bridge. The principle scheme of measurement is given in fig. 3.

A two-steps method of recording was applied. The value at the instant of the blow was registered directly on the magnetic-tape recorder, and next reproduced on the UV-recorder. This method was adopted to remove from the records troublesome vibrations that followed the blow.

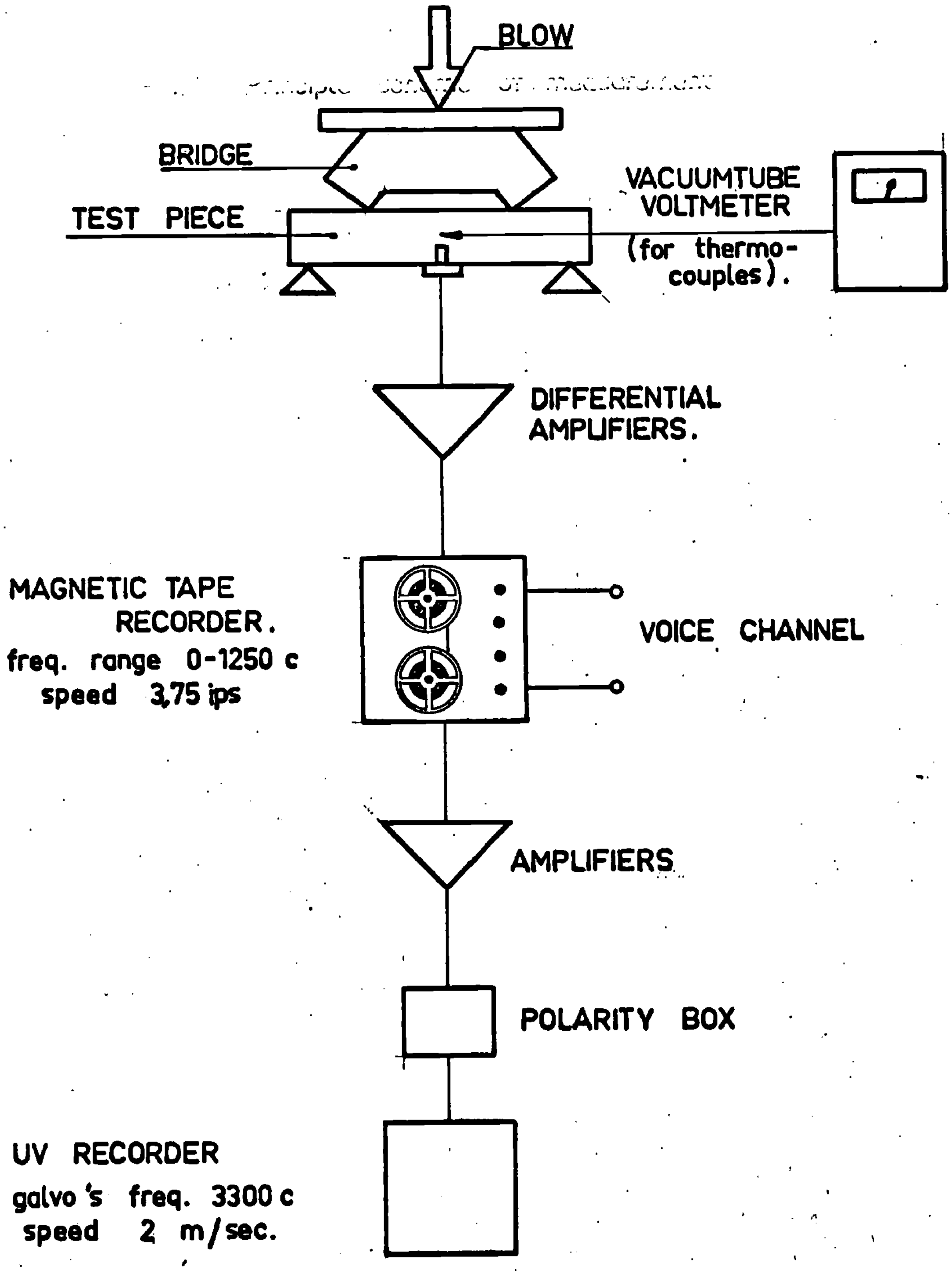

FIG. 3. Principle scheme of measurement.

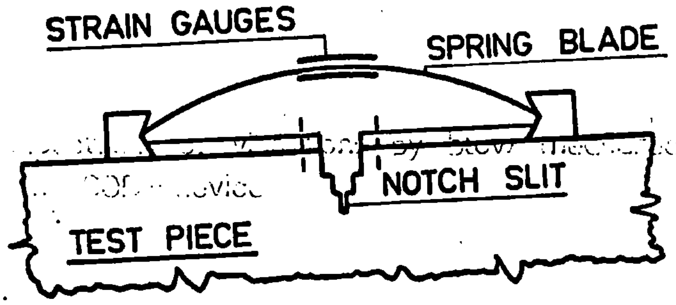

FIG. 4. Bridge gauge for COD measurements.

FIG. 5. Spectrum of vibrations by blow measured on COD - device.

Fig. 3.

3. <u>The dynamic COD-measuring problems.</u>

Simple instrumentation in the form of a flat spring with strain gauges on it, fixed in supports (fig. 4) is in use in the Delft S.S.L. for the COD-measurements.

Fig 4

Other sources /2, 8/ mention special clip gauges in the form of two small cantilever beams with strain gauges on them, attached to the edges of the notch slit.

Both solutions are suitable to determine the COD value for tests in conditions of slow rate loading. A first trial to adopt the COD-device like on fig. 4 for impact tests indicated the complexity of this problem.

The energy of blow by impact loading is taken over in a very short time by the test-specimen, which deflects in an elastic or elasto-plastic manner.

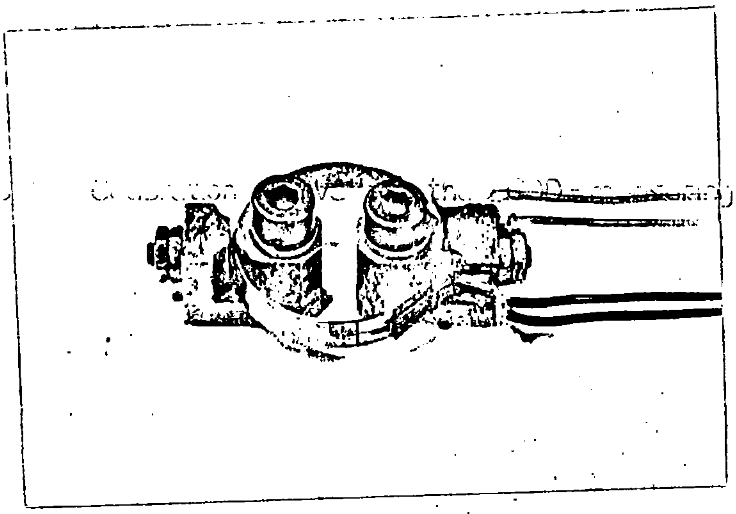

FIG. 6. COD-measuring device used for the impact tests.

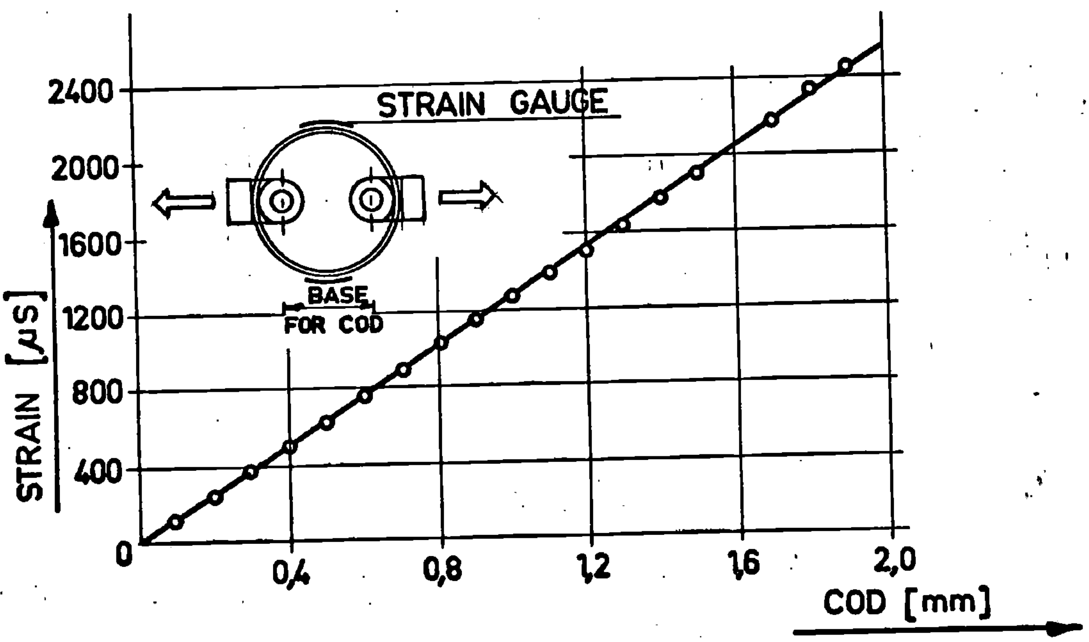

FIG. 7. Calibration curve for the COD-measuring device.

High accelerations occurring in this process cause extremely severe conditions for every mechanical system. The first trials proved that the high inertia forces induced big deflections of the spring, and this jumped out of the supports. Stiff connection of the spring-ends to the specimen did not resolve the problem because of vibration phenomena. The dynamic COD value being a function of the test-specimen deflection, could not be determined because of the very complicated spectrum of vibrations registered simultaneously by the strain gauges on the spring (fig. 5).

Fig. 5

The spring vibration amplitude was reduced by applying the spring with its plane in a perpendicular position relative to the specimen-surface, i.e. in the position of the greatest stiffness in relation to the direction of the inertia force. To avoid resonance effects (giving particularly unreadable records), it was necessary to increase the natural vibration frequency of the spring. For this aim reduction of the length of spring was not the solution, because this goes with a not desired reduction of the COD measuring range. The problem was resolved by applying a ring-spring with appropriate diameter instead of a flat spring (fig. 6).

Fig. 6

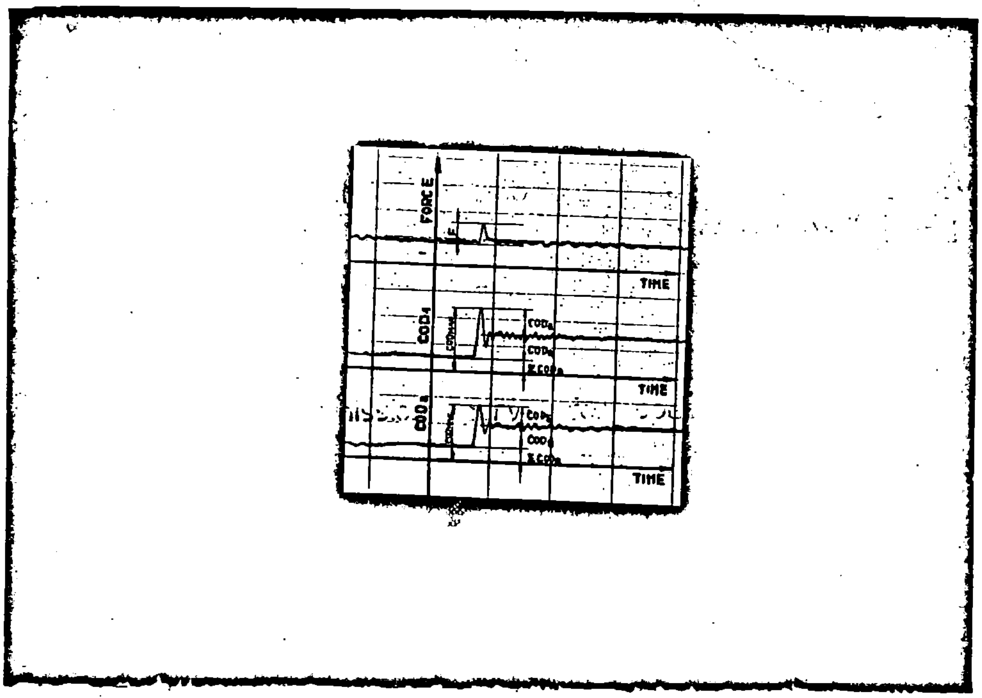

FIG. 8. Example of record COD-value and impact force by blow.

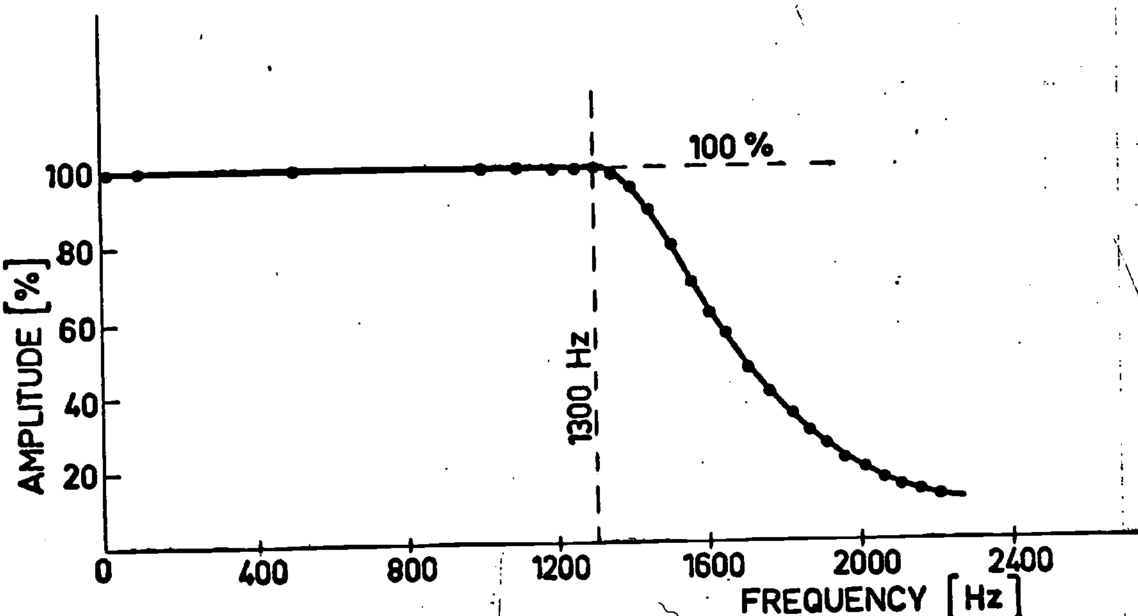

FIG. 9. The transmission curve for speed 3,75 ips.

Such a ring-spring by its large natural frequency showed good linearity in the required range of COD-values (fig. 7).

Fig. 7

The vibrations with increased frequency of the spring which disturbed the measured COD-value was eliminated by the method of recording on a magnetic tape recorder, with limited transmission frequency. From the magnetic tape, records without not-desired vibrations were reproduced on the UV-recorder (fig. 8).

Fig. 9

This method of filtering was relatively simple, however not perfect, because of the not very sharp characteristic of the transmission curve for the chosen speed of recording (fig. 9). In the case considered, the natural frequency of the spring was about 3000 cycles/sec. The effect of cutting out vibrations by a lower speed of record was better, but caused reduction of maximum values of COD (fig. 10).

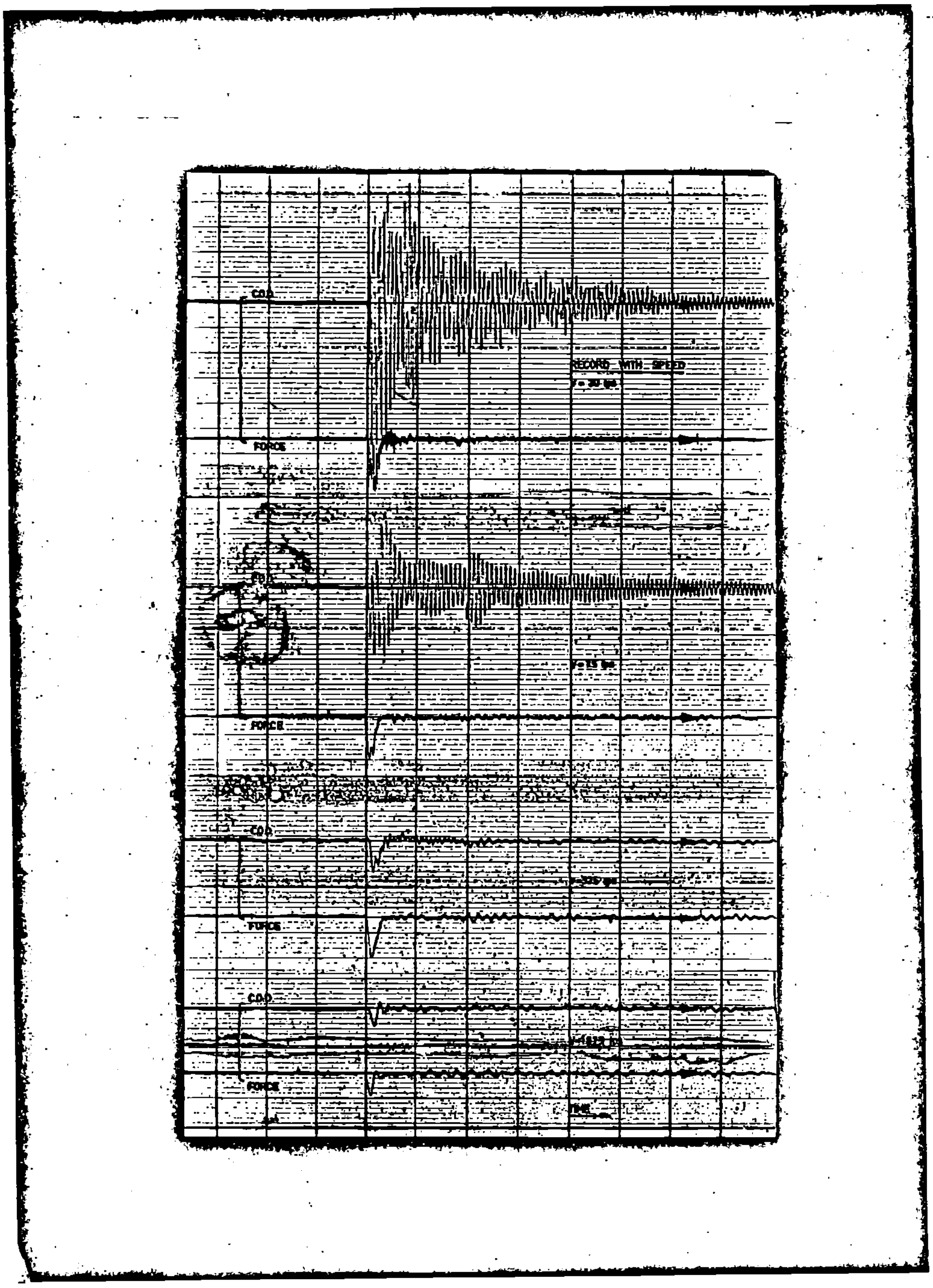

FIG. 10. Examples of a record of the same spectrum of vibration at different speed.

Fig. 9.

Fig. 10.

Of course the method described is not unique. By use of a special filter with a more abrupt damping characteristic it is possible to obtain very fair records. For the investigations carried out, the use of a magnetic tape recorder was fully satisfactory, considering the relative simplicity of such a method.

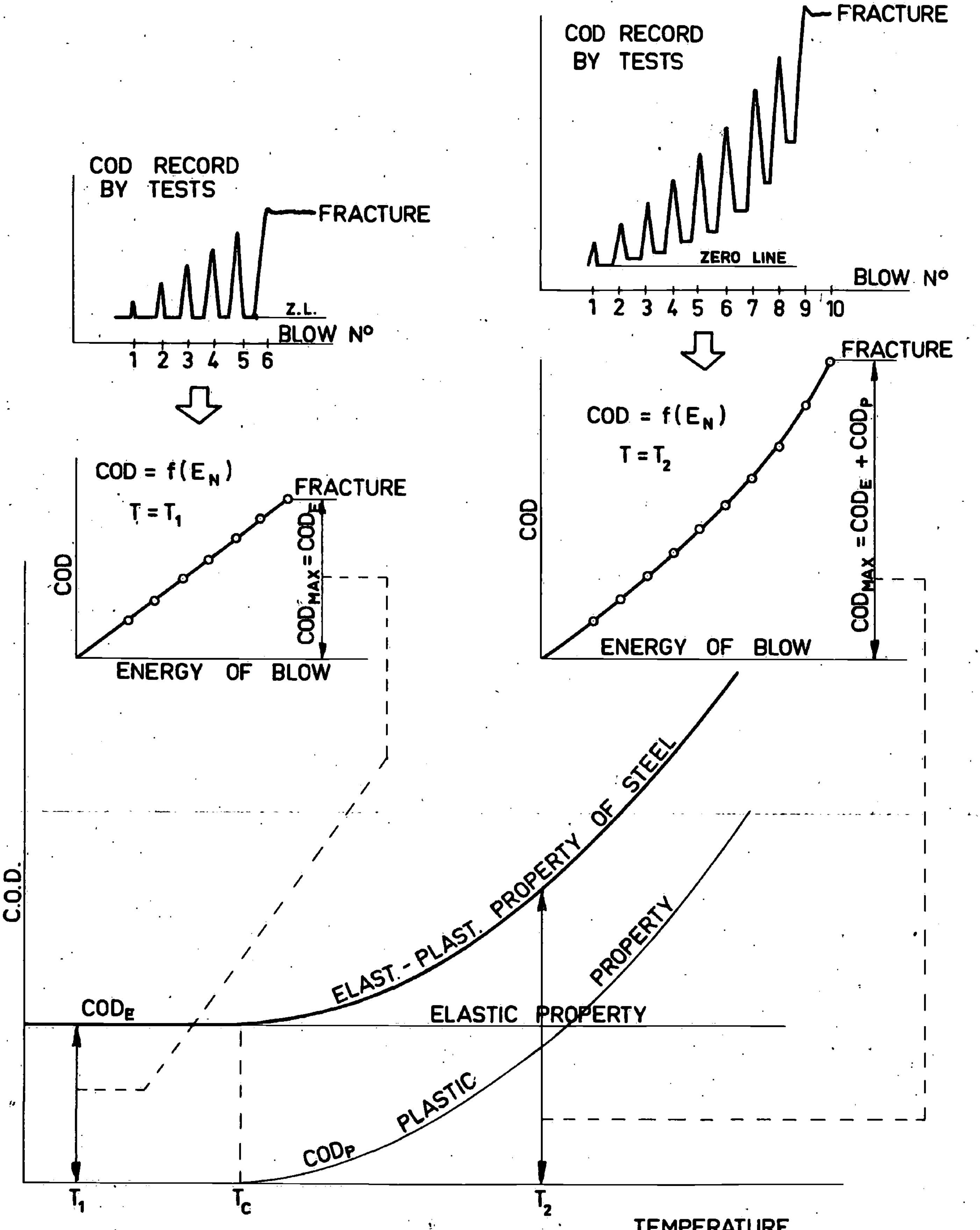

FIG. 11. Schematic ilustration of elastic and plastic property of a steel as a function of temperature expressed in COD values determined by impact tests.

determined

4. Determination of material properties by dynamic COD measurements.

The first structural response on a loading is always elastic, because in crystal, there is only one mechanism of energy accumulation in the form of elastic strain between atomic bands. If the amount of energy supply to any part of a structure is higher than the critical value for this case, the excess of energy causes plastic deformation or fracture.

Elastic deformation as reaction on a loading is always three dimensional in such a mode, that when in one direction the distance between atoms is increased, simultaneously in the two other directions this distance is reduced. This unsymmetry causes a change in the primary state of balance between atoms, and by loading increase there are possibilities of reaching the point of instability when space dislocations of particular atoms to new positions of balance give better structural accomodation to loading. This dislocation process is known as plastic deformation and this valuable property of a material protects a structure for sudden damage by excessive loading. This property is limited and under some conditions may be quite impossible. In such circumstances increase of loading leads to increase of elastic deformation and without plastic recombination, a critical distance between atoms is reached by which tearing of atomic bands occurs. This phenomenon is known as brittle fracture, which is extremely dangerous for a structure.

Between these two extreme phenomena, there are all kinds of intermediary modes of rupture, classified as normal fracture combined with plastic flow.

Plasticity properties of steel are reduced by a limited freedom of displacement, by three-axiality in tension, by low temperature and by high speed of loading. All these conditions can be simulated by impact tests on notched specimens.

The big advantage of the impact tests with consecutive increase of energy of blow carried out at different temperatures, is the possibility to separate two essential properties of steel, and to assess these by measuring of the COD. These two properties are: critical value of elastic deformation (COD_E) by fracture without plastic flow - this corresponds to Griffith-Irwin's value of K_C called the fracture toughness /9/, and the magnitude of plastic recombination as a function of temperature (fig. 11).

Fig. 11.

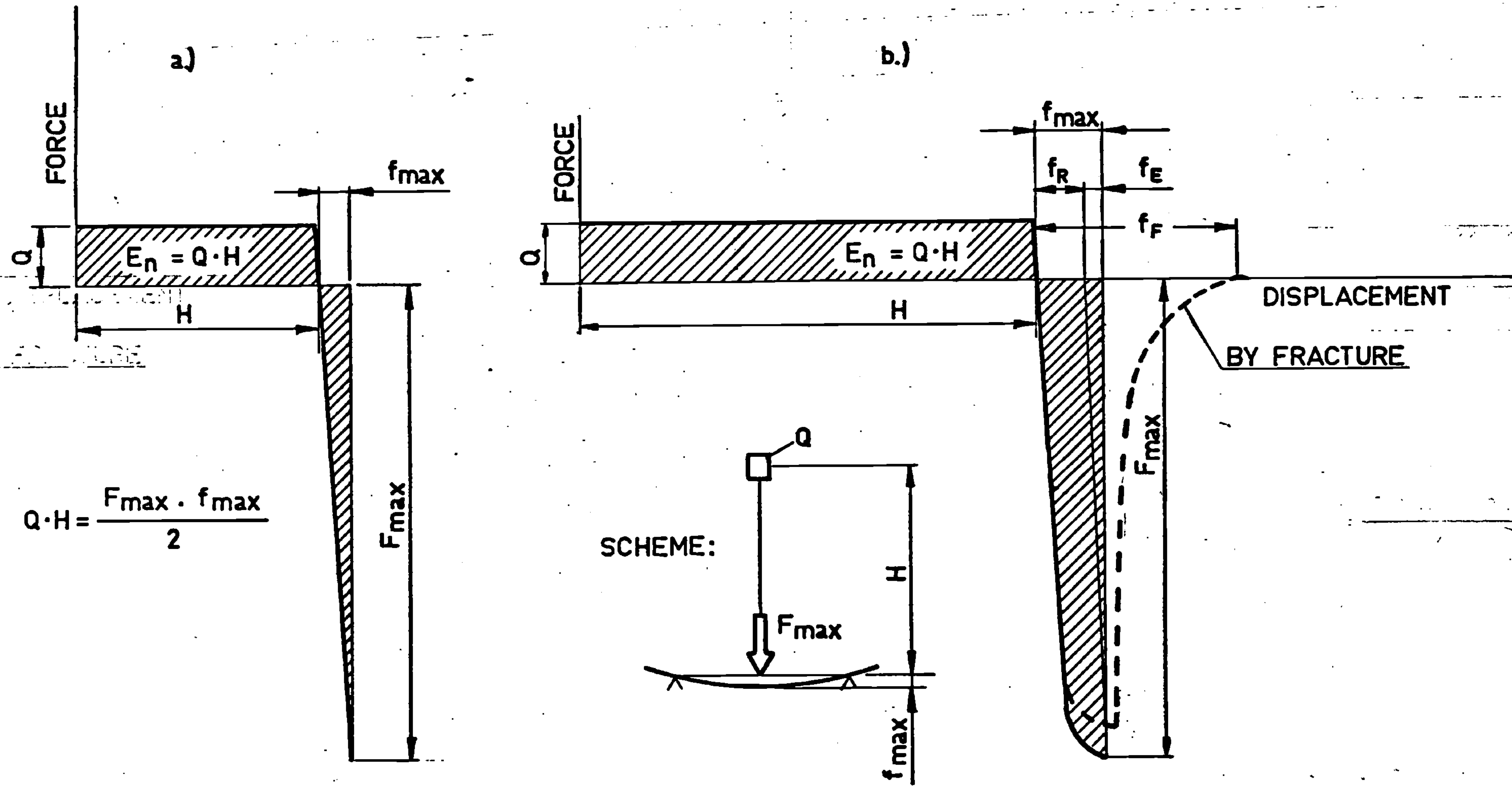

FIG. 12. Correlation between energy of blow (E) , testpiece deflection (f) and force measured on bridge (F) by :

a) pure elastic deflection
b) elasto-plastic deflection.

The parameters such as yielding and fracture stress, tendency to brittle fracture and fatigue resistance (which are of special interest to designers) are functions of the above mentioned two properties.

5. Examples of measurements of dynamical COD and force by impact tests.

By impact loading, the energy of blow causes dynamic deflections (fd) of the test-specimen. This value correlates with the dynamical COD measured in the region of the notch. The magnitude of the force leading to deflection of a test-piece is depending on the stiffness of the specimen and mode of deflection (pure elastic, elastic-plastic, or with fracture). (Fig. 12).

Fig. 12

If plastic deformations appear in the region of the notch, the specimen shows a residual deflection, which is not linear to the corresponding residual value of COD (fig. 13).

A sample record of COD-values from UV recorder for consecutive blows to fracture is shown in fig. 14.

It should be noticed that there is not a constant relationship between the deflection of the specimen and COD, and these two values must not be understood as equal. The COD-value regards local conditions in the vicinity of the notch, while a deflection more defines circumstances valid for all specimens. These differences are evident on the diagram obtained by the static tests, regarding deflection and COD-value by increased loading (fig. 15).

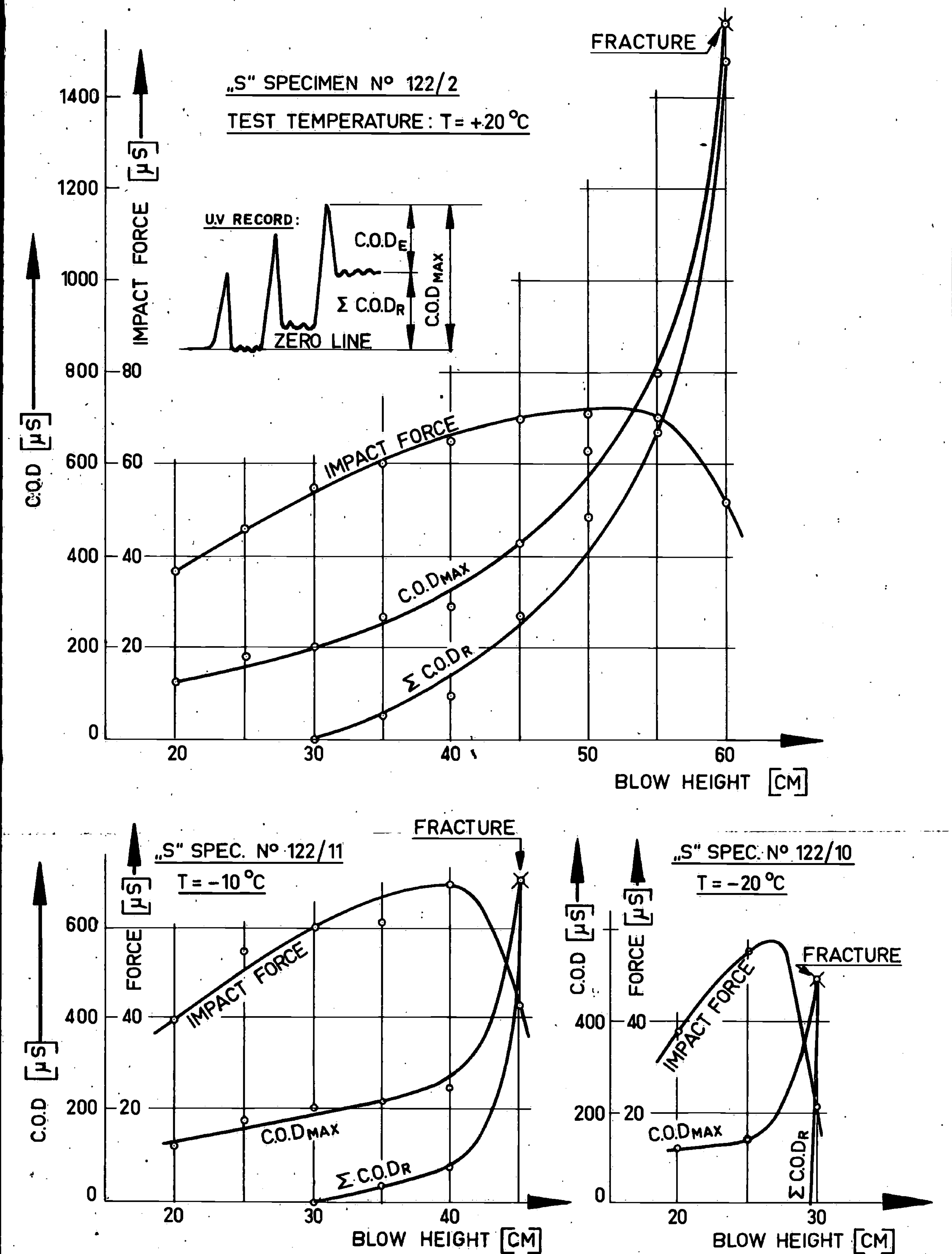

FIG. 16. Comparative diagrams of COD, and impact force as a function of blow energy, from tests at different temperatures.

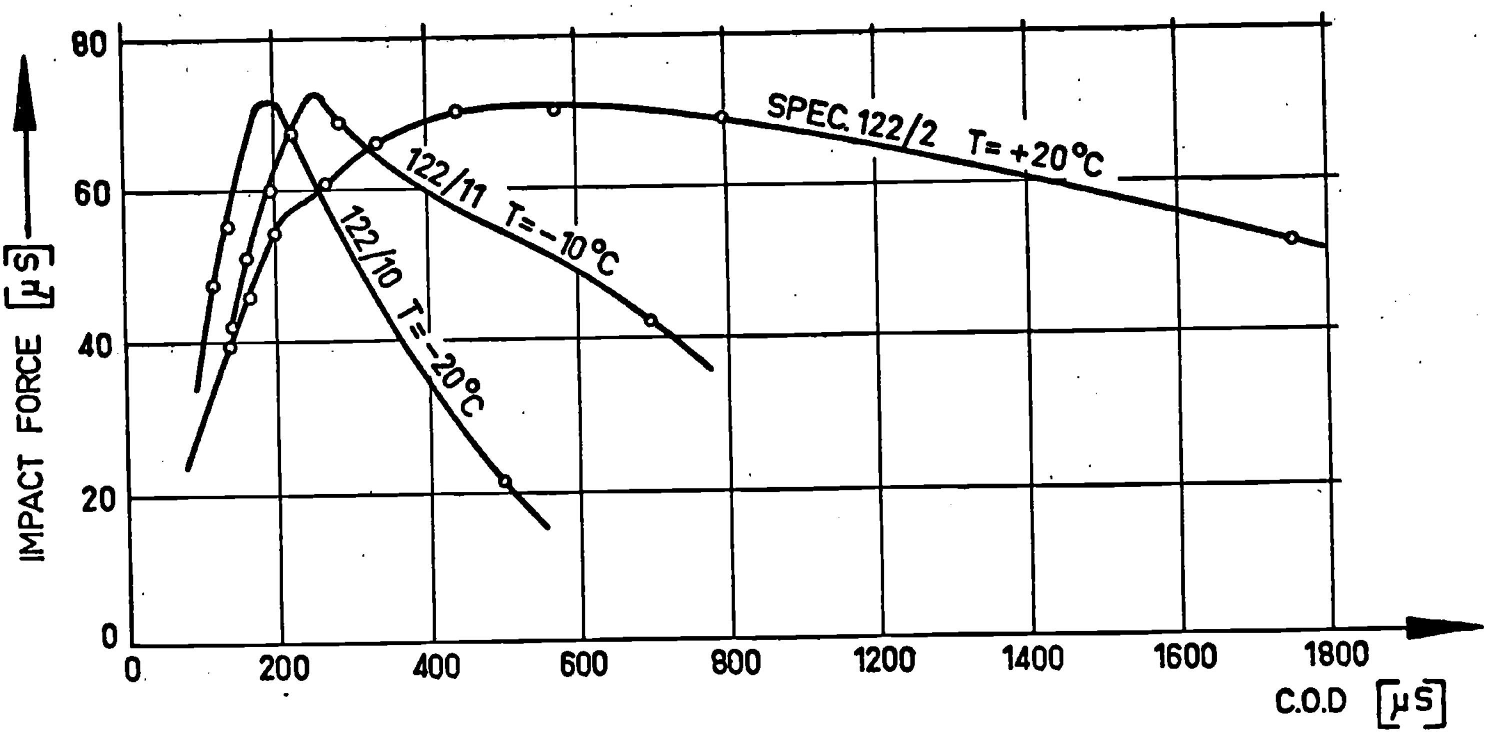

FIG. 17. Comparative diagrams: impact forree versus COD, from tests at different temperatures.

The values of COD_{max}, COD_E, COD_R and impact force, put in a diagram as a function of blow energy, suit well for further analysis. Such diagrams from tests at different temperatures clearly indicate the above mentioned (fig. 11) differences between elastic and plastic properties of a steel (fig. 16).

Fig. 16

These relations can also be expressed in diagrams which directly indicate the dependencies of impact force (F_{max}) and COD. (Fig. 17).

Fig. 17

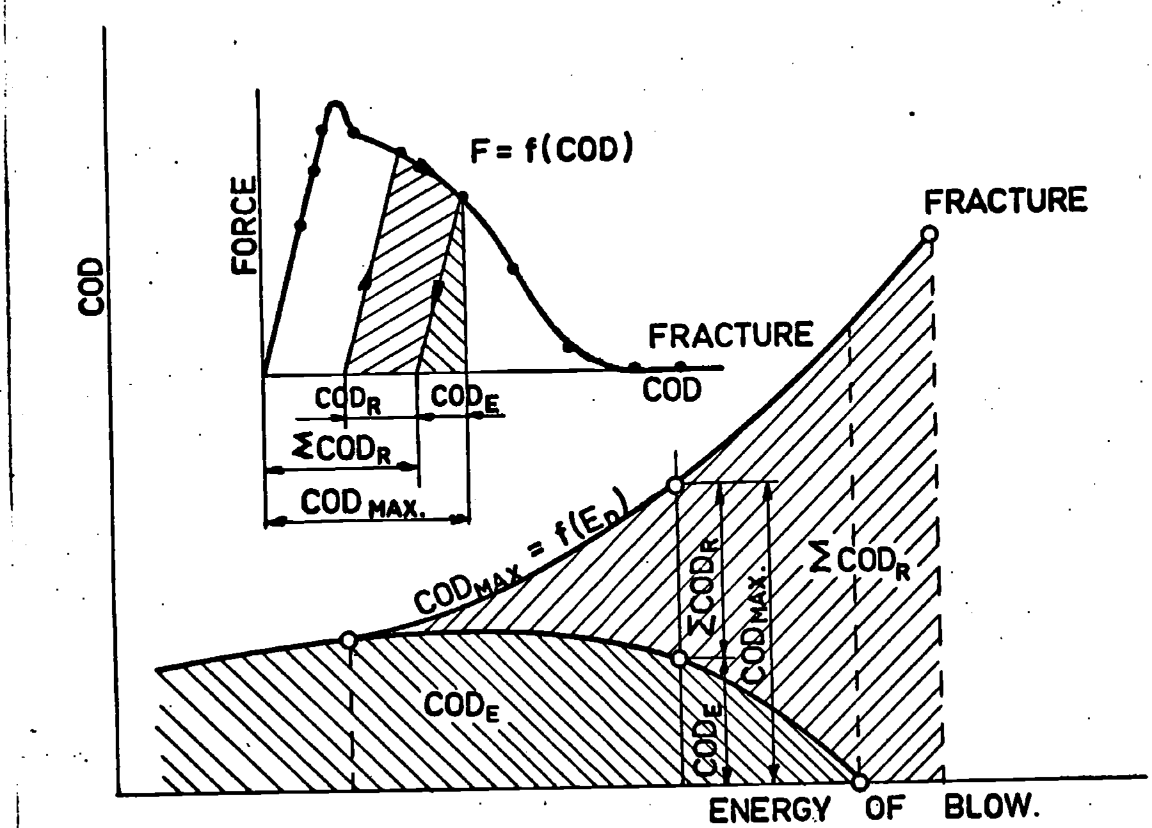

FIG. 18. Schematical diagram of $COD_{max.}$, COD_E and $\Sigma\ COD_R$ till fracture.

It is worth to remark that the COD_{max} value at fracture is equal to the sum of residual COD-values ($\Sigma\ COD_R$). By step-wise increase of impact loading, we can distinguish three phases in COD_{max}. (Fig. 18):

1) when $COD_{max} = COD_E$;
2) when $COD_{max} = COD_E + \Sigma\ COD_R$;
3) when $COD_{max} = \Sigma\ COD_R$.

Fig. 18.

The fracture point on the above diagrams is only approximate and simply it is the point of the last blow, at which a more or less advanced crack occurred. It seems that the beginning of the crack is in close relation to the phenomenon of apparent decrease of the elastic COD-component. But this last phenomenon is undoubtedly influenced also by the Bauschinger effect because of the fact that, in the vicinity of the notch, the material is plastically deformed while the rest of the notch cross-section is only elastically deformed.

It is remarkable that the maximum COD by fracture is almost the same as the residual COD. This observation confirms that the NIBLINK test procedure may be appropriate as a method for material quality control. In such a case usually we look for the dependency of the plastic property on the temperature. This can be shown on the diagram $COD_F = f\ (T)$. (Fig. 19).

In all above considerations, the usefulness of dynamical COD-measurements is discussed regarding the properties of steel as a parent material. From the designer's point of view often more interesting are properties of welded connections. Obviously the method of COD-measurement on notched

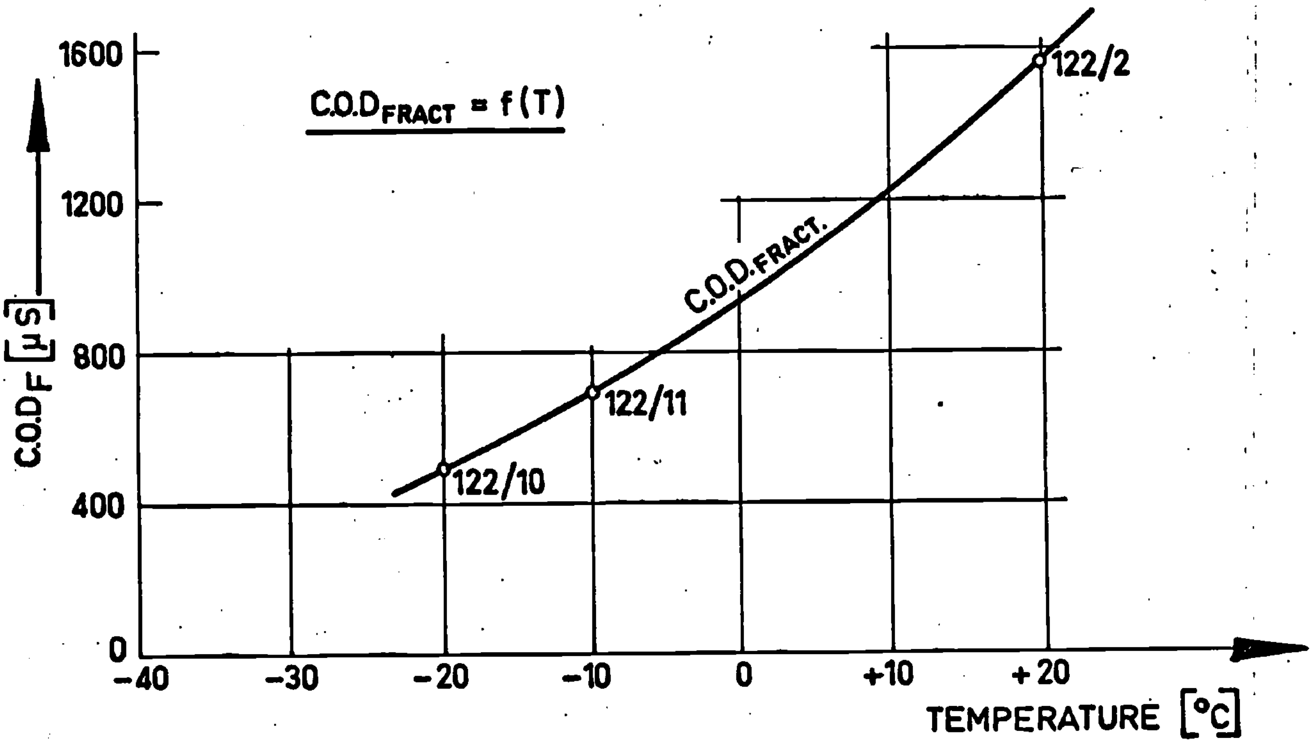

FIG. 19. Sample diagram of COD_F by tests at different temperatures

Fig.: 19.

specimen is especially suitable for such investigations and there are no objections against the use to assess properties of welds.

6. Conclusions.

Measurements of the dynamical value of COD by impact tests are useful to assess basic properties of steel and especially the disposition to brittle fracture initiation.

Such measurements may be interesting for investigations regarding the improvement of the quality of steel as well as to check strength properties of parent material and weldments for different kinds of steel.

Acknowledgement.

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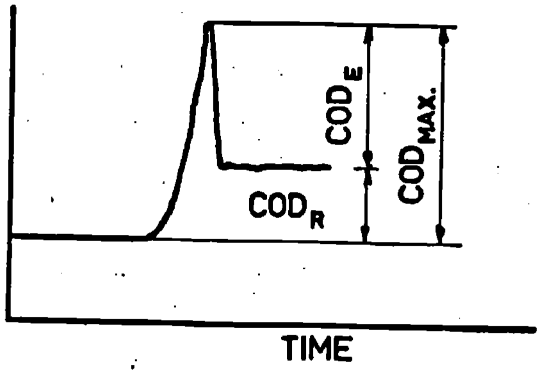

FIG. 13. Values measured from dynamical record of COD.

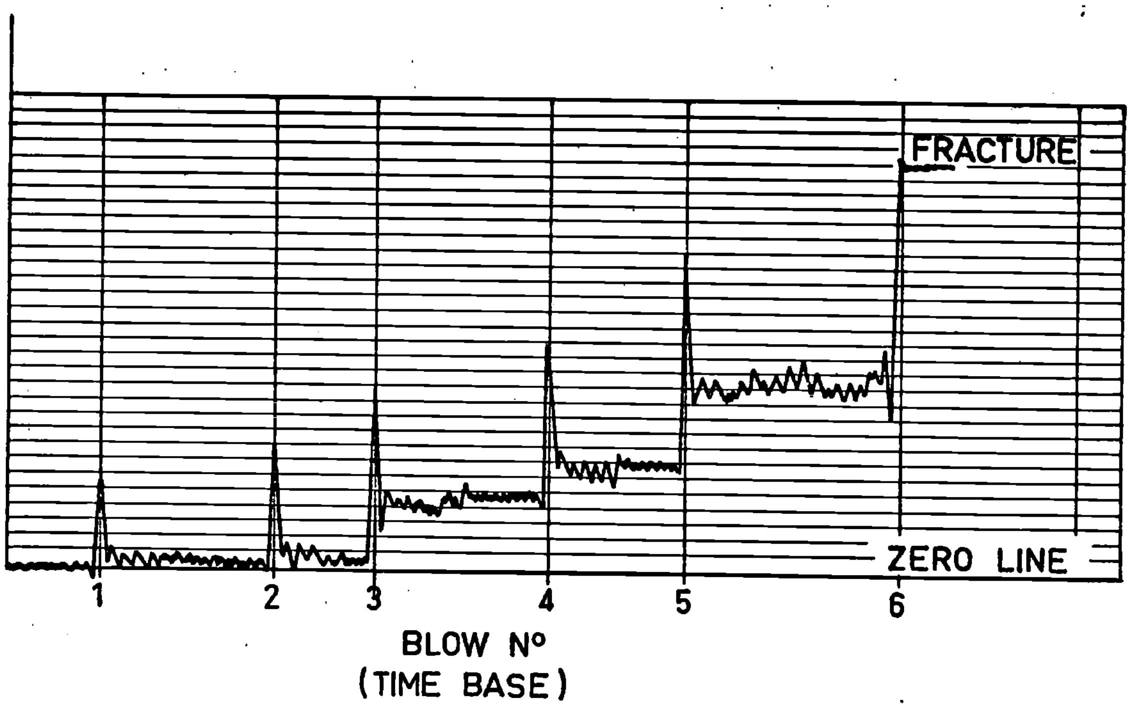

FIG. 14. A sample record of COD values by consecutive blows.

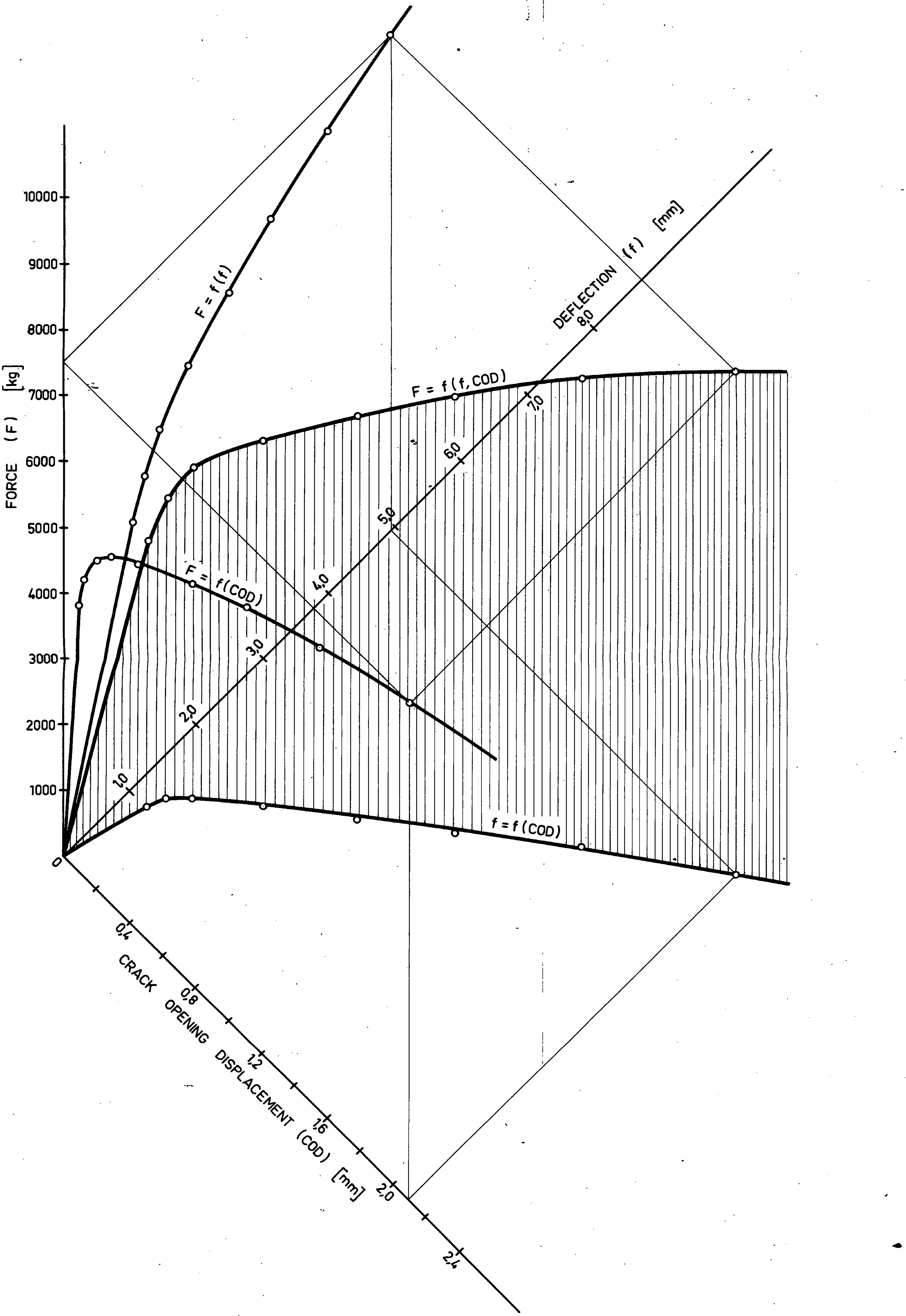

FIG. 15. Dependency of deflection, COD and loading force, by static test.