Effects of Residual Stresses on the Behavior of Structures

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Editorial Abstract

The author begins by discussing three spontaneous fractures along the webs of I-beams, the ends of which had been flame-cut some hours or days previously. He then selects four cases of failures of structural elements which he considers typical of failures largely due to residual stresses, and discusses these briefly.

There follows a critical section on the measurement of residual stresses.

In a section on the origins of residual stresses it is pointed out that from the point of view of applied mechanics there is no difference between macrostresses and microstresses. Direct (local) welding stresses and reaction stresses and their effects are discussed.

The latent energy represented by direct welding stresses is not considered of primary importance, but the author indicates that the energy associated with reaction stresses may be high and of grave importance.

Residual stresses superpose with other stresses in exactly the same way and to the same degree as different stresses from other sources superpose. It must be remembered, however, that residual stresses may change, as under conditions of fatigue. Attention is called to a possible large effect on the system of stress as a whole by variations of temperature throughout the structure.

The question is raised whether cracks have to be initiated, whether in fact they do not exist from the beginning and merely have to be propagated. In the propagation of cracks latent energy is considered to play an important role.

Reference is made throughout the paper to pertinent examples in the author's experience.

1. Examples of Fractures in which Residual Stresses Played a Role

The first example to come to the attention of the author which awoke his interest in residual stresses and their effects on the behavior of structures occurred on March 9, 1934. A beam (PN 55) of high tensile strength

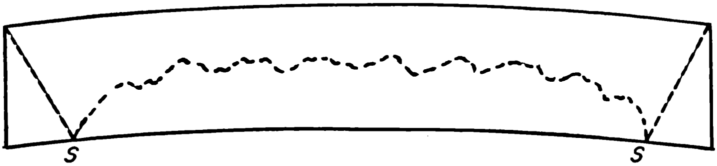

FIG. 1

steel (58 to 65 kg. per sq. mm.), 12 m. long, fractured spontaneously in the shop under no load. On the day before, skew cuts had been made at both ends (Fig. 1) with a cutting torch. The beam was lying flat on the ground. The fracture occurred along the whole length through the web, during the noon hour. The violent noise gave the impression of an explosion. Workers thought that a tank of compressed air had burst. The appearance of the fracture was very rough and jagged, with a generally coarse and crystalline granular structure. Along most of the length, there was a kind of longitudinal wrinkle in the middle of the fractured web.

The temperature was normal. Both parts of the beam were curved, showing an outside concavity of the flanges, with deflections of 8 and 7.5 cm. (Figs. 2 and 3). Tests were made on a specimen cut from the central part of the web, which gave normal results. The beam was one of a large series of identical beams to be used in the steel structure of the Laboratory of Thermodynamics of the University of Liège, which the author had designed. No other beam suffered any damage.

There was no question of welding, but there had been flame-cutting. The only possible explanation of the fracture and the curvature of the two parts is the existence of rolling stresses. The web cooled much more quickly than the flanges. The web was perhaps cold-worked to a certain extent by rolling (although the tests on the web, namely, the notched-bar impact test, showed no evidence of cold-working). The thermal shortening of the flanges by cooling was prevented by the web, which induced high stresses in the beam and a large amount of elastic potential energy. This created a state of precarious internal equilibrium. Actually it was the flame-cutting

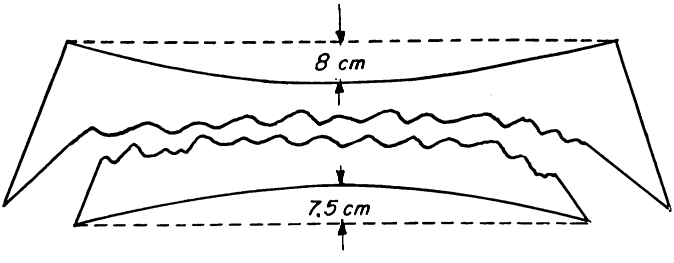

FIG. 2

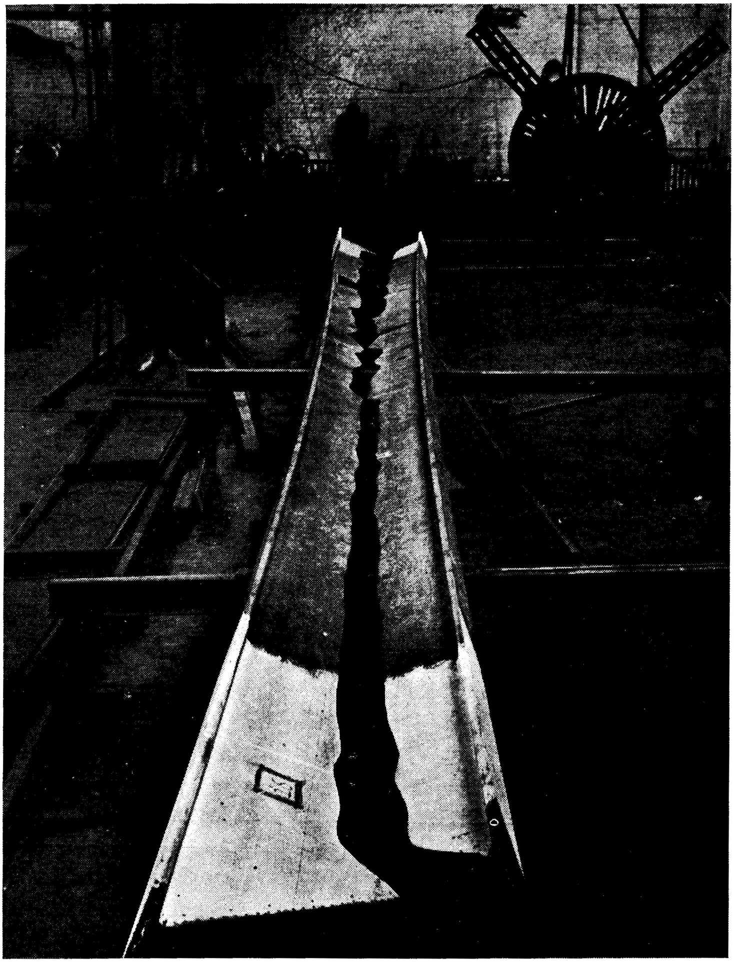

FIG. 3

which changed this state of equilibrium, but with no immediate effect; nothing happened for 24 hours.

The initial state of residual stress was a consequence of the thermal history of the various parts of the beam, of its shape and dimensions, and of the mechanical properties, elastic and plastic, of the metal. Undoubtedly plastic deformation may have occurred because of the restraint produced by the unequal cooling, and local strain-aging and hardening were possible with the corresponding increase in elastic limit, already rather high for this kind of steel under normal conditions. Thus, rolling stresses, although purely elastic, may have been high, as also the elastic energy of deformation stored in the beam. Along the lines of the skew cuts at the ends a certain distribution of residual stresses existed, which were relieved by the cuts. This is equivalent to the application along the lines of the cuts of a reversed system of loads superposed on the initial distribution of rolling stresses—roughly to the application of two appreciable compressive forces along the flange at the points *S* (Fig. 1). This changed the initial state of internal equilibrium and may have done so in a dangerous manner. This is all easy to understand and no other explanation seems possible. The only obscure point is the delay of 24 hours before the fracture. This lapse of time, often much longer, seems to occur in all similar cases. A possible explanation is that flame-cutting generates the beginnings of cracks, aided with time by the state of rolling stresses. These cracks must have grown slowly, until the final stage of equilibrium was reached. Existence of cracks, often rather deep and rather old (rusted in the course of time) in collapsed welded bridges, observed by the author, seems to establish that the generation, the existence, and perhaps the development or propagation of cracks are possible in actual structures. But the structures in which the author observed them had been subjected to numerous and repeated loadings, which was not the case of the beam.

It is possible that, under the heavy state of residual stresses and the action of heating by the flame followed by cooling, a kind of artificial strain-aging and hardening was produced locally with corresponding decrease of the specific energy of fracture after a certain time. The great amount of elastic energy stored in the beam then produced the fracture. Once the fracture was started, the distribution of residual stresses changed almost instantaneously, as the phenomenon was rather explosive in character. Thus dynamic forces may have been developed in a rapidly transient form and a complicated process of fracture may have taken place, leading to the result shown in Fig. 3.

The case of the beam was not an isolated one. In the same shop, the author was shown a wide-flanged Grey-beam from Differdange (Fig. 4) in which a similar, but more regular crack, not extending quite to the end of the beam, occurred after a small cut at the ends of the flanges. The rivet holes show that the beam was to be riveted; there was no question of welding. The manager of the shop told the author on the same occasion that a similar limited crack had occurred at one end of a beam in the riveted structure of a neighboring electrical power plant, some two or three years after erection. Thus there was no question of welding here either.

Further inquiries revealed that such accidents, though rare, occurred from time to time in the rolling mills or in the erection shop. People in general were not much interested, and usually these facts received no publicity, so that nothing or little was known about them outside.

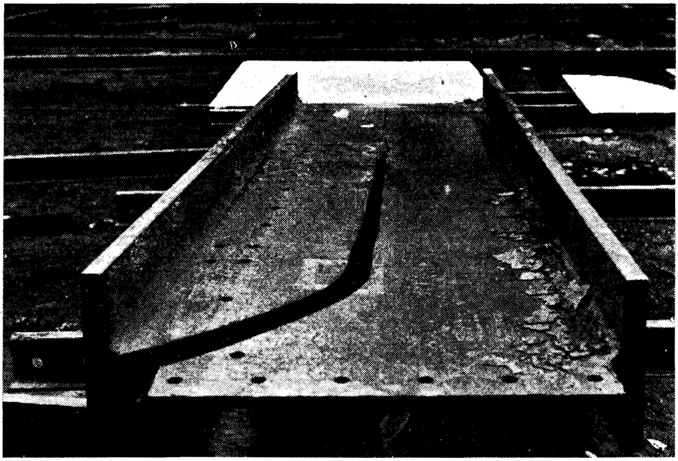

FIG. 4

Fig. 5 shows a similar fracture in a beam of normal strength, 360 mm. deep. This specimen is still in the author's collection. The fracture does not extend throughout the whole length of the web. The mechanism of the phenomenon is the same for Figs. 3, 4, and 5, in each case rolling stresses and flame-cuts at the ends, the magnitude of the stresses being indicated by the opposite curvatures of the two flanges. The author believes that these are three examples of fractures (and there must exist many more of the same kind in the world) in which residual stresses played an essential and decisive role. The author has published these cases and many others, including photographs, since 1936 (International Congress of Bridge and Structural Engineering, in Berlin)[1, 2].

It may be emphasized that these examples occurred previous to the development of welding.

The development, which led in Belgium to the construction of a large number of heavy structures and bridges between 1932 and 1938, had as a consequence that fractures with the characteristic appearance shown in Fig. 3 occurred frequently rather than seldom and they rapidly required the attention of specialists. They received wide publicity after the first total collapse of a bridge in March 1938. At the beginning of 1936, a joint group of structural and bridge engineers and of the official Board for Bridges and Highways (Administration des Ponts et Chaussées) charged the author with the investigation of the difficulties already met in the shops and with research work to overcome them. First of all, the author proceeded to an inquiry into the facts. He assigned this inquiry to a young civil engineer, Mr. H. Louis, and a report was presented to the joint group in October 1936. Thereupon it was decided to keep the report continuously

FIG. 5

up-to-date and to begin an extensive program of research on shrinkage and other effects of welding. Mr. Louis was appointed to the Board for Bridges and Highways in November 1937, and he continued to keep the report independently. This report has never been fully disclosed, but extracts have been given at times after the war in lectures by Mr. Louis, namely, before the International Institute of Welding, in 1950 (Paris)[3].

The late Mr. G. De Cuyper, Chief Engineer and Head of the Bridges Bureau of the Board of Bridges and Highways, published some of the principal items in this report in a paper for the Third Congress of the International Association for Bridge and Structural Engineering, in Liège, in 1948[4]. His paper showed clearly that he was not disposed to emphasize the role of residual stresses in the failures described, which led the present author to make some remarks before the Congress[5]. The author refers the reader to these papers and will discuss only a few cases taken from the paper by Mr. De Cuyper.

(a) Failure at the beginning of 1936, in the shop. Temperature about 0°C. Thomas steel (42 to 50 kg. per sq. mm.). A wide plate 300 by 30 mm., roll-formed cold to a radius of 1500 mm., cracked during erection before any welding was done. Thus there was no question of welding. The only possible explanation is that the residual stresses induced by the forming were responsible for the spontaneous failure of the plate, which was hardened by cold-working and strain-aging. But the fracture is unthinkable without the action of stresses or stored elastic energy whose source can only be residual stresses.

(b) Failure in June, 1935, in the field during erection. Temperature above 10°C.

A Siemens-Martin plate (37 to 44 kg. per sq. mm.) AA (Fig. 6) was welded as a joint plate between two elements of a post of Thomas steel (37 to 44 kg. per sq. mm.). First the lower fillet welds were made, then the upper. During the last welding, the plate failed in the thickness, the laminated structure of the plate being revealed by the fact. The only possible cause: shrinkage stresses as admitted by Mr. De Cuyper.

(c) Failure in March, 1938 (at Hasselt) of a bridge in service more than a year, but carrying no live load when the failure occurred. Nor-

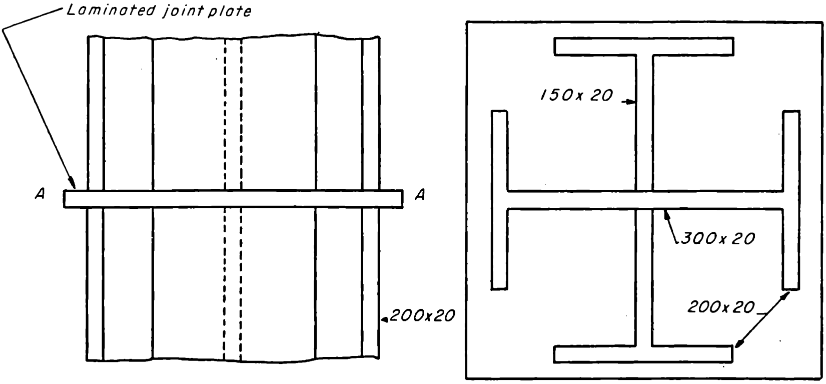

FIG. 6

mal temperature. Thomas steel (42 to 50 kg. per sq. mm.). Failure of the lower chord of the bridge (Fig. 7). Probable mechanism of the fracture: the weld connecting the attaching pad to the curved flange was the last one to be made. Thereby the foot of the post of the Vierendeel truss became in effect a hanger. The large weld had defects, namely, at the root, not having been backed on the side of the root (this was almost impossible). The failure of this hanger produced a sudden strain of the underlying lower chord. Cause of the fracture (according to the opinion of Mr. De Cuyper, designer of the bridge): residual stresses, very severe because of the large weld at the attaching pad. The action of these residual stresses was favored by the defects of the welds and other defects.

The existence of these residual stresses and their importance was

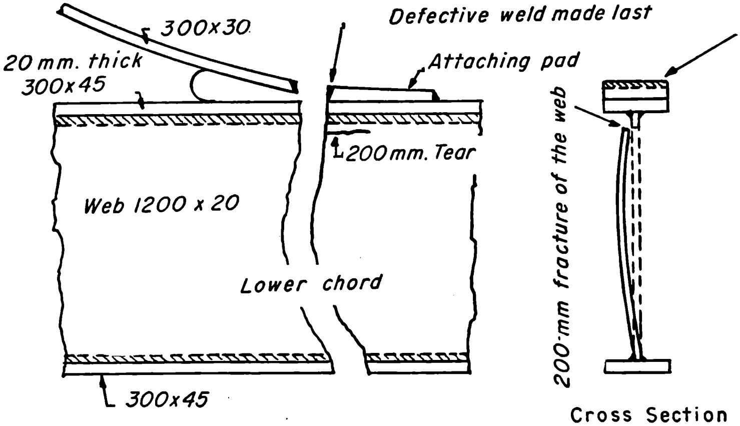

FIG. 7

proved by observations made on the collapsed bridge and on others of the same kind, ordered by a committee of investigation (of which the author was a member) instituted by the Government. Many welds of the same kind as mentioned above were cracked. These cracks can only have been caused by residual stresses. In order to release the residual stresses, it was decided to saw-cut the welds of the above-mentioned kind in the similar bridges. This operation was performed on a great number of welds in many bridges with the following general effect: after a more or less substantial cut, the piece fractured with a noise. The remaining cross section at the moment of the fracture allowed some estimation of the residual forces involved, which were very high.

(d) A last example of failure occurred in the summer of 1939, on a bridge in service. Normal temperature. Siemens-Martin steel (52 to 60 kg. per sq. mm.). Crack in the lower flange and in the web of a plate girder. Brittle fracture. The butt weld in the flange had been made before the fillet weld connecting the web to the flange (Fig. 8). Cause of the failure: residual stresses, with stress concentration caused by

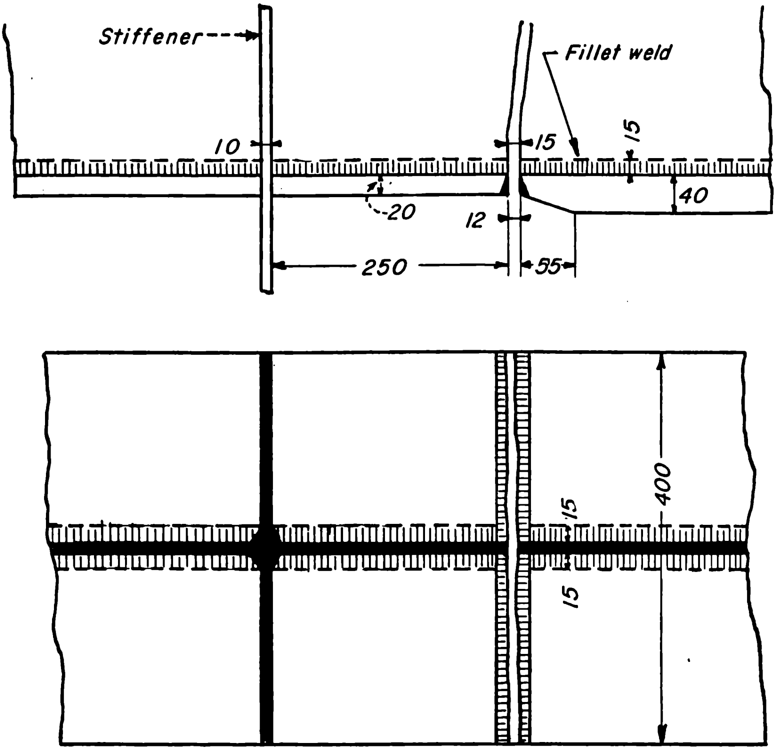

FIG. 8

the very sudden change in thickness of the flange, and defects in the weld.

These are a few examples taken from among a fairly large number having the same features in common. The author has in his collection many specimens of collapsed or damaged bridges and also cracked parts.

As the "Proposed program for the preparation of a monograph on residual stresses"* indicated that contentions that residual stresses have a significant effect on load-carrying capacity are backed by little, if any, experimental evidence, the author found it expedient to present first some of the many cases of evidence of the decisive role of residual stresses on fracture.

The author has also much evidence obtained by artificial experiments in which cracks were generated in welds, evenutally extending into the base metal because of welding stresses due to restraint. The "proposed program" adds that evidence supporting the conclusion residual stresses do not contribute materially to failure has been obtained from laboratory investigations on simulated hatch corners. The question arises whether these laboratory investigations allow conclusions about anything else than the conditions and circumstances of the investigations. Namely, is there evidence that the conditions of residual stress in simulated hatch corners may reproduce the stresses locked up in ship structures as the result of fabrication practice, and especially is the elastic energy stored in these ships simulated and able to act on the hatch corners?

The author, however, must confine himself to the presentation of facts of which he has firsthand knowledge, as they have taught him that each case requires particular investigation and study.

2. Measurement of Residual Stresses

According to Lord Kelvin's principle, it seems that the best evidence of residual stresses may be obtained by their measurement. In fact, such evidence may be obtained by various techniques of measurement, some of which will be discussed further.

In the author's opinion these techniques of measurement call for some reservations with regard to their conformity to the principles of applied mechanics. But this point will not be considered here, as being outside the subject. It is mentioned only to emphasize that the measurement of residual stresses requires still more caution than the measurement of ordinary stresses. The measurement of residual stresses often has more the qualitative significance of a proof of the existence of residual stresses rather than the quantitative significance of a precise determination. In other words,

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* The reference is to a program sent to prospective contributors when they were asked to submit papers. Ed.

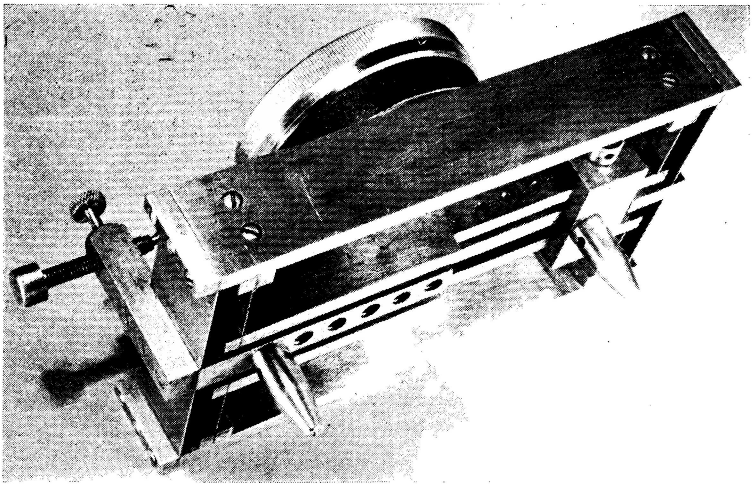

Fig. 9

it is difficult to evaluate and to verify the degree of approximation; the measurement indicates rather an order of magnitude.

The author has put in practice the so-called relaxation techniques of measurement since 1938 (ref. 2, pp. 70–80). For welded test plates used in the laboratory, the destructive method of cutting in small pieces on which four gage lengths at 45° have been marked on the two faces is very reliable. The author has generally used a gage length of 20 mm., the pieces being 25 mm. square. The measurement is made with mechanical deformeters, manufactured by the author's laboratory, whose sensitivity is less than 0.001 mm. The measuring legs are provided with set-in calibrated balls (since 1942), which makes the measurements much easier and more accurate than with the conical pins used formerly on similar commercial apparatus. Fig. 9 represents a type now in use with adjustable bases of 12, 20, 40, 80, and 100 mm. Provision is made at present for a smaller and lighter model with a gage length as short as 10 mm., perhaps less.

This destructive method of cutting is not expedient on actual structures. Therefore, since 1939, the Schmuckler apparatus of the author's laboratory was equipped, at the request of Mr. H. Louis, with a hollow drill capable of cutting out of structures cylinders 27 mm. in diameter to a thickness of 30 mm., allowing the same measurements as by the preceding method (ref. 2, p. 103). Some measurements of residual stresses were obtained by this "trepanning" method on welded bridges. The hole was left open or filled with a bolt. Nevertheless, trepanning an actual structure offers some difficulties, and it seemed advisable to drill smaller holes with ordinary portable drills. The author's attention was attracted to the principle of Mathar's apparatus. The author's former tests to control and calibrate Mathar's apparatus had proved the imperfection of this device, both systematic and practical. Therefore, during the war, the method was modified in this way: a 10-mm. hole was drilled and the measurements were made along four gage lines at 45°, 20 mm. long, whose centers coincided with the center of the hole. The drilling of the hole affects the lengths of the gage lines. Measurement was made with a device such as represented in Fig. 9. The mathematical treatment of the drilling method is given in ref. 2, pp. 103–109. Later on, when resistance strain-gages became known in Belgium, Professor Soete used a similar method, with strain gages disposed outside the hole in radial directions. Now the author measures on gage lengths of 12 mm. with 6-mm. holes. Rather extensive measurements were made during the winter of 1949–1950 on the hulls of two large ships (a tanker and a cargo vessel) during their erection and welding in the shipyards of John Cockerill and Co. at Hoboken (Belgium), under very difficult conditions and in very bad weather. The device used was that shown in Fig. 9, with a 12-mm. gage length for the measurement and holes 6 mm. in diameter. The results were fairly good. Strain gages used as alternatives failed generally because of the rough conditions. These extensive tests were made on behalf of the Belgian Center of Naval Research. The values of some of the measured stresses were very high[10].

The cutting method is very convenient for systematic laboratory work and may be fairly precise, even with simple and efficient devices such as that of Fig. 9. The trepanning method is also convenient for laboratory work, especially for isolated tests, with the same level of precision as for the cutting method. The drilling method is much less precise and, in the author's opinion, to be recommended only for work on actual structures, in the field or in the yard. The above-mentioned relaxation techniques must be used for the measurement of residual stresses in a destructive or semidestructive way when the strain in the material has exceeded the elastic limit. Otherwise, in the laboratory as in the field or the yard, measurements may be made by such a device as shown in Fig. 9 without any destruction. Then the stresses are based on the consideration of the purely elastic deformations produced by the process whose effects are to be measured, just as is usual for the measurement of ordinary stresses.

Based on an experience of some twelve years with the various relaxation techniques, destructive, semidestructive and nondestructive, the author has formed the opinion that the measurement of residual stresses is undoubtedly of great intrinsic interest, but rather delicate and tiresome. This is the case even in the laboratory under the most favorable conditions, but especially outside under bad conditions, and when the plate cannot be placed horizontally and turned to measure on the other side, it being necessary to make the measurement in the position presented by the actual structure. To the author's mind, these are just the most interesting measurements, as in his opinion, laboratory specimens do not reproduce the effects of general residual stresses in big structures, which depend on the whole structure. He believes that rather simple and easy to handle mechanical devices as in Fig. 9, of sufficient accuracy, and not excessive sensitivity, are capable of giving the best practical results—results that are perhaps more reliable than those obtainable with electrical strain gages when the working and climatic conditions are very rough.

There is naturally no objection to the aim of improving the sensitivity and the precision of the measuring devices, but this aim may prove to conflict in some cases with the practical conditions of the measurements.

Nevertheless, it must be borne in mind that the significance of the measurements is affected by the great variation of nonuniform stresses in the region of the measurement, for example, in the close neighborhood of a weld. It must also be borne in mind that the repetition of loading, which is generally used in the measurement of ordinary stresses to check the good working order of the measuring device, is excluded here.

Other techniques have not been tried by the author. The use of some of them in the field and on actual structures seems questionable to him. He has also not had experience with X-ray techniques, but he nevertheless thinks it worth while to draw attention to a quite different discrepancy from the one mentioned above, which may affect measurement of stresses by X rays. The question is whether the definition or conception of stress according to classical applied mechanics, implying continuity of the material, holds good on the atomic scale, which is the scale of X-ray measurements. Some fundamental questions of applied mechanics or of the physics of solids or of both as boundary problems, may arise from this, which are outside of the author's field of activity.

3. Origins of Residual Stresses

The author has observed many origins of residual stresses and above has given examples of some: forming operations, welding, differential cooling rates, cold-working, permanent or plastic deformation, restraint of deformations and phase transformations of some alloyed metals. He is in agreement with common opinion concerning these origins.

Perhaps the situation is not the same concerning the question of order of magnitude, or is it only a matter of words and convention? In the author's opinion, there are no micro- and macrostresses; there is only one kind of stresses, complying at every point with the ellipse of stress. The stress at a point is a tensor, and a point is neither micro- nor macro-. Perhaps the author should apologize for such remarks, but he has so frequently met disregard of the most fundamental principles of applied mechanics in questions dealing with residual stresses and effects of welding in general, that he may have grown somewhat sensitive about it.

Concerning the stresses produced by welding, the author has considered elsewhere[2] the so-called *direct welding stresses*, which are developed in every case, even when the welded piece is completely free. These stresses are localized in the neighborhood of the weld and decrease rapidly on both sides of the weld. They could also be called *local welding stresses.*

When the welded piece is not free, but restrained in its thermal deformations, the effects of welding produce so-called *indirect welding stresses*, which affect the piece everywhere; they might also be called *reaction stresses.* They exist together with the direct or local welding stresses. The author has experimented with the simple device of a rigid frame in which the ends of two flat bars are "built in," the two other adjacent ends being welded together. In the neighborhood of the weld arise the nonuniform direct stresses, and at the same time the test piece is subjected throughout its entire length to more or less high uniform indirect stresses. If the piece is subsequently cut out of the frame, the latter stresses disappear and only nonuniform direct or local stresses remain.

The stresses considered above are those existing in the permanent final condition. They can be measured by the methods considered in the preceding section. Naturally, these stresses are developed during the welding process, so that one may also consider transient welding stresses of direct or indirect character (ref. 6, pp. 232–236). Their measurement is not possible and little is known about them; but there is no evidence that they are not more significant than the final and permanent stresses, and the possibility should not be excluded that they generate more cracks than the final stresses.

The separation of direct and indirect stresses is not always so easy as in the simple case considered before. For example, if a welded beam is made by welding together a web and flanges and, furthermore, stiffeners are welded to the web, a rather complicated system of residual stresses may occur, in which the distinction between direct and indirect stresses holds good, but their discrimination becomes difficult. It will depend eventually on the sequence of the various welds. A recent observation of Mr. H. Louis showed that the welding of vertical stiffeners to a web some 8 to 10 m. long produced a shortening of the web of 5 mm. Hence it is advisable to weld the stiffeners to the web before the web is welded to the flanges.

A common property of residual stresses is that they are purely elastic, even if they result from plastic deformation. They may be released by all the operations which release the elastic deformations corresponding to the residual stresses, with consequent dissipation of the elastic potential energy stored in the material. But this may be accompanied by plastic deformation and new residual stresses. For example, in the case of the first beam considered previously (Figs. 1, 2, and 3), the large curvature of the two parts of the beam involves plastic deformation and residual stresses in the two parts, quite different from those existing before the fracture.

4. Latent Energy in Structures Containing Residual Stresses

The elastic character of residual stresses involves the storage of elastic potential energy. Although the actual deformation may exceed the elastic range considerably and the residual stress may eventually exceed the yield point, nevertheless, the residual stress is purely elastic, just as occurs in unloading (Fig. 10). For example, in the case of uniaxial tension, if σ_1 is the residual stress, the hatched area represents the part of the energy necessary to reach this stress, which has been wasted, and the area of the triangle $1\delta_1R$ represents the conserved potential energy.

Hence, in the general case the potential elastic energy per unit of volume is:

$$W_1 = \frac{1}{2E}(\sigma_x^2 + \sigma_y^2 + \sigma_z^2) - \frac{\nu}{E}(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x) + \frac{1}{2G}(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2).$$

In the case of direct or local welding stresses, their mean value is well under the elastic limit, as they decrease with the distance from the weld. The volume involved is limited and, consequently, there is not a large amount of energy stored up. Furthermore, this energy is enclosed in a limited volume without possibility of transfer. Its liberation is perhaps impossible without external physical means, as for example, by annealing. Or it may be liberated through cracks, generally of limited development corresponding to the liberation of a limited amount of energy restricted to a small volume.

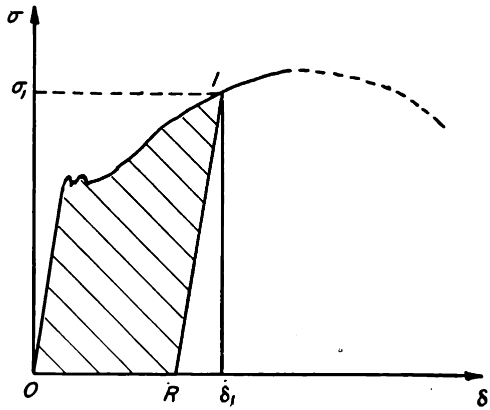

Fig. 10

In the case of indirect or reaction stresses, their value may be high and be stored in a rather large volume; but they may develop their effects in any part of this volume, however small. If we consider the case of the welded bar in the frame mentioned before, we may cut the bar progressively till it breaks; at this moment all the potential elastic energy is dissipated when the fracture occurs. The same occurred when cuts were made in the welds of the attaching pads in the welded bridges mentioned above. If there are cracks or other important defects, all the stored energy acts on these weak spots and may lead to fracture. In the case of uniaxial tension:

$$W_1 = \frac{\sigma_1^2}{2E} = \frac{E\delta_1^2}{2} = \frac{E(\Delta l)^2}{2l^2}.$$

For example, Δl is the restrained deformation, or shrinkage, in the length l. If ω is the area of the cross section, the total energy will be $W = E(\Delta l)^2\omega/2l$. As Δl does not depend on l, or not much, and may be large, this energy will be the larger, the smaller l is. In the case of the example (c) mentioned before of the bridge at Hasselt, the considerable restraints affected small lengths, and the potential elastic energy must have been rather high in a rather small volume. In the case of the beam of Fig. 3, it is obvious that a fairly large amount of elastic energy was stored and liberated by the fracture. It resulted in noise (which does not dissipate much energy), probably in heat, and partly in remaining elastic potential energy due to the new redistribution of residual stresses.

Experience shows that this energy can remain latent for a long time, being only more or less dissipated by special and adequate processes, such as annealing or mechanical plastification.

5. Reaction of Residual Stresses and Working Stresses

The author has often received from practicing engineers, if not the definite opinion, at least a general impression that residual stresses are not of the same nature as others, such as stresses produced by external loads. He believes that it is unnecessary to refute this opinion in this monograph. According to the classic definition of a stress in applied mechanics, residual stresses and working stresses act just the same as any other stresses do. If their combined effect remains under the elastic limit, the principle of elastic superposition applies. If, on the contrary, this limit is exceeded, then plastic flow takes place, according to the properties of the particular material, without regard to the special kind of stresses. Because of the plastic flow, the residual stresses will not be the same as before. A redistribution of stress takes place.

For example, in the above-mentioned welded bar in the rigid frame, a high degree of residual stresses is produced by the combination of direct welding stresses in the neighborhood of the weld and the indirect or reaction stresses produced by the restraint. But if the bar is cut out of the frame, only direct welding stresses remain. Their measurement shows that they are much smaller than the similar stresses in a bar welded without restraint if the general stresses have reached the elastic limit, and of the same magnitude if this limit has not been reached (ref. 2, pp. 77–91). The redistribution is easy to understand and shows that direct welding stresses in a bar may be considerably reduced by stressing the bar beyond the elastic limit. But it must be borne in mind that a condition of high stress exists during the overstressing and that the mechanical properties of the bar may be considerably altered by this process.

When the overstressing is produced by indirect or reaction stresses, as is the case for the welded bar in the rigid frame, or for the foot of the post of the Vierendeel bridge mentioned in Section 1 as example (c), the effect remains permanent and strain-aging develops during the same time. Hence the elastic limit may be increased and the necessary energy to produce fracture may be decreased per unit of volume (Fig. 11). When, furthermore, some gometrical conditions, such as cracks, notches or others, prevent the major plastic flow of necking and reduce still more the energy necessary to produce fracture, this may occur as the result of locked-up residual stresses or their latent energy. The effect of time is obvious in this process and explains the delay of fracture in some cases.

In other cases, the effect of time may be associated with the frequent repetition of external loading, producing frequent small deformations (fatigue) which may alter progressively both the residual stresses and the mechanical properties of the metal (ref. 2, pp. 131–149). If high permanent stresses exist, fracture by fatigue may occur under a rather low number of

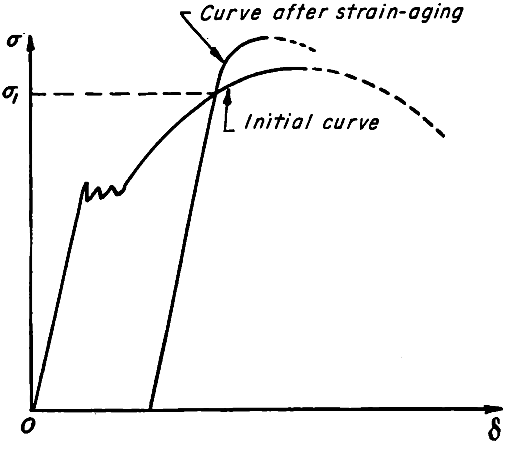

FIG. 11

repetitions of a very small additional stress when the test piece is more or less weak in fatigue, for example, because of cracks, notches, and other similar defects or misfits.

In an actual structure, the general high stress may be produced by reaction stresses. The author believes that this is the main cause of the collapse of the Belgian welded bridges in 1938 and 1939, as also of the German bridges, such as the Rüdersdorf bridge (1938). Generally they collapsed when unloaded, which resulted happily in a general absence of victims. Most of them had been in service for more than a year, and they had supported test loads and afterwards much heavy traffic. The bridge at Hasselt, for example, was used for more than a year and had supported heavy test loads. A few days before the collapse, a bicycle race, very popular in the country, crossed the bridge, which was crowded with citizens of the neighboring town. If the collapse had taken place under this load, the number of victims would have been catastrophic. The morning of the collapse, a light tramway vehicle, a bicycle, and a few pedestrians had just crossed the bridge when a violent report was heard and the bridge broke in two parts and fell into the canal. There was no external circumstance to explain the failure at just that time. The bridge, however, not only had high residual stresses at the foot of each post, but also two large and bad welds at each foot.

Furthermore, no provision had been made for shrinkage, which was high, because of the rather large thickness of the plates and large V-welds. The parts of the bridge were therefore all too short and, consequently, there were gaps which had to be filled with welds. Thus the welds became very large and produced more and more restraint and a general state of high residual stresses. The whole bridge was, in a sense, loaded with latent energy, somewhat explosive; furthermore, it had many defects, most of them of a serious nature. The small fatigue effect of the live load continued the inexorable process of fracture till the end.

There are indeed confilicting opinions about the effect of residual stresses on fatigue strength. Some say there is no influence, others believe the influence is important. In fact, both are right and there is a misunderstanding because residual stresses are considered without discrimination between direct or local stress and indirect or general stress.

For example, in the case of direct stresses in the neighborhood of a weld, the repetition of load results in a redistribution of stresses by repeated small plastic flow. This process reduces the residual stresses more and more and finally the resistance to fatigue is not affected. But this is only the case for local stresses with little storage of energy.

In the case of high indirect or reaction stresses, locked up in a large volume with a large amount of latent energy, this redistribution is not possible; the pulsating stress is superposed on a high general stress which makes the conditions of fatigue worse. Then it happens that resistance to fatigue is reduced, so much the more if the welding has some defects.

This may also occur in the cases mentioned before where the distinction between the direct and indirect residual stresses is not sharp, as in beams formed of welded plates. In questions that are so complicated, no general simple rule can be stated. Each particular problem must be investigated and eventually tested according to various possibilities.

The effect of low temperatures has often played a role in fractures resulting from residual stresses. The part played has generally been discussed with respect to the behavior of the materials, namely, the effect of low temperatures on brittleness and the so-called critical temperature. But indeed, the effects of temperature changes on heavy structures, generally highly statically indeterminate and with dispositions of material which enable temperature differences between various parts, may be dangerous. Especially if the existence of high general residual stresses has locked up a large amount of latent energy, if strain-aging and hardening has taken place, if dangerous defects exist in the welds or other parts and if fatigue has, according to the previously described process, generated the progressive process of fracture, it is easy to understand that extreme temperature conditions, with the general shortening resulting from severe cold, may produce the additional effect sufficient to start the final stage of fracture. This should not be surprising at all since such failures have occurred at normal or summer temperature, as shown by the examples of Section 1. It is not excluded that the low temperature affects the metal and reduces the energy necessary for the fracture, but the author believes that it is difficult to prove it and, in any case, it is not permissible to disregard the active effect of residual stresses.

The first big case when the effect of low temperature required attention was the collapse of the German bridge at Rüdersdorf in January, 1938. The collapse of the Duplessis Bridge, between Quebec and Montreal, on January 31, 1951, seemed to reproduce the same facts many years later on a larger scale but under apparently similar conditions, although according to the accounts available in the technical press, the Canadian bridge must have been built less carefully than the German one[7].

6. Effects of Residual Stress on Initiation and Propagation of Fracture

The author has left this question for the end because it is very much unresolved and subject to controversy. Again the discrepancy between the classic conception of stress, according to applied mechanics, and the atomic structure of the material, according to the physics of solids, must be emphasized. The whole theory of fracture based on the resistance of materials is questionable. What is the very initiation of a crack? It must occur on an atomic scale, out of the reach of applied mechanics. In a sense, applied mechanics excludes the possibility of studying the phenomenon of fracture, because the basic assumption of continuity is violated; fracture creates discontinuity. Hence arguments about this problem are rather precarious. It is generally admitted that fractures are localized by the defects of the materials on various scales. The so-called dislocations are defects on an atomic scale. The author believes that there is a large probability of effective defects on a larger scale, although microscopic or even submicroscopic, but often also macroscopic: skin defects, segregation, inclusions, defects at the boundaries of the grains or in the grains, small cracks called "criques" in French, fisheyes, etc.

So it is questionable whether the cracks have to be initiated or whether their beginnings already exist. The microscopic examination of so-called smooth surfaces is edifying in this respect. In any case, the author finds it more expedient to limit himself to the propagation of cracks which evidence presented in the previous sections has indicated can be produced in various ways by residual stresses (see for instance, Figs. 3, 4, and 5). This ability is especially important for indirect or reaction stresses, with much latent energy, although direct or local residual stresses, with little energy, are eventually able to produce small and limited cracks. This ability results from the fact that cracks, by their geometrical shape of extremely acute notches, not only produce high stress concentration, but also prevent large plastic flow and, consequently, do not require very much energy for fracture. Hardening by strain-aging resulting eventually from the plastic deformations which have produced the residual stress, with increase of elastic limit and ultimate strength but decrease of energy absorption, may contribute to the propagation of cracks.

The author has shown in the preceding section that fatigue superposed on high permanent residual stresses is particularly able to produce propagation of cracks. So he believes that there are many ways in which high residual stresses, helped by other causes, may contribute to the propagation of cracks, or even cause the propagation completely by themselves, as in the case of Figs. 3, 4, and 5.

Perhaps it is of interest to report a very peculiar case in the author's experience[8]. Rails were tested in fatigue by pulsating bending, the top being in compression. The highest stress was in the top and was therefore compressive. Then there was no fatigue fracture, but cracks were produced in the compressed top. In one test specimen three cracks were formed, one after 4.3×10^6, the second after 5.2×10^6, the third after 6.6×10^6 repetitions. After 8.856×10^6 repetitions the system remained perfectly elastic and the test was ended. *The cracks were closed under load and open when unloaded.* The explanation is easy. The high compressive stresses in the top produce plastic shortening of the top at each loading. Hence the top is too short when unloaded and residual tensile stresses are produced. The action of these tensile stresses produces the cracks. In fact, by the action of the pulsating bending and the consequent residual stresses, the test under repeated bending stress is changed to a test under alternate bending stress (tension and compression). But the cracks here have another peculiar character; they release the residual tensions and make the test piece invulnerable. Many rails have shown the same very interesting cycle of redistribution of internal stress and adaptation. It may be mentioned here that similar static observations have also been made, for example, on the cracking of the hooks of reinforcing steel used in reinforced concrete, when formed by cold bending (cf. "Bericht über Versuche mit Verankerungs-Endhaken an Beton-Armierungseisen," by Th. Wyss, Zurich, in *Premier Congrès International du Béton et du Bétone Armé,* Liège, 1930, vol. 1). These cracks start in the compressed zone and are produced by the effect of residual stresses arising from the heavy plastic flow of the compressed zone.

The author believes that these examples are very elegant indications simultaneously of the generation of residual stresses, of their reaction with working stresses, and of their decisive role in the propagation of cracks.

7. Conclusion

The author has been very much interested by the initiative of the Committee on Residual Stresses of the Division of Engineering and Industrial Research of the National Research Council of the U. S. A. He is thankful for the opportunity offered to him for a larger diffusion of some observations and researches which have been going on for some eighteen years. His warmest wish is that they may contribute to clear the important problem

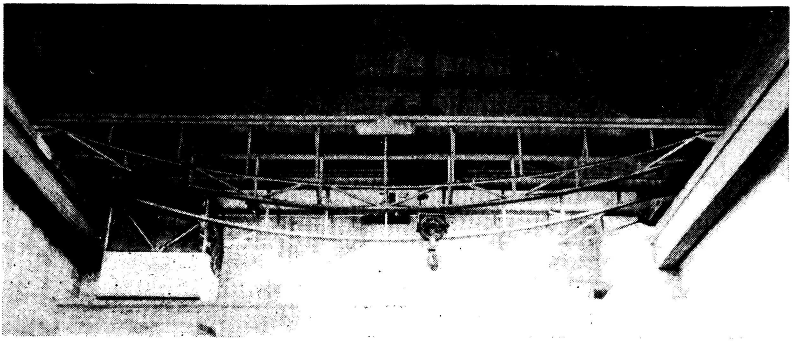

FIG. 12

under consideration. The elucidation of this problem will not only be a scientific achievement but will prove to be of far-reaching engineering interest. Not only will it make it possible to avoid the bad effects of residual stresses, but, used with skill, it may render residual stresses one of the useful links in the general method using controlled stresses in design, which the author has empahsized previously[9]. Prestressed concrete, for example, is only a limited application of this general method.

The author has discussed elsewhere the useful control of residual stresses in a travelling crane for heavy duty, which he designed (ref. 6, p. 247). The parabolic lower chord of the bow-string girders was made of flat bars with a weld in the center. This weld was reserved for the last and the whole chord was preheated. The subsequent shortening due to cooling and shrinkage of the lower chord stressed the girder and was taken into account in the design. At the same time, the preheating favored the quality of the weld. A similar highly dynamic welded structure, which has been in use without incident since 1937, is shown in Fig. 12.

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