STEEL EVALUATION OF VEHICLE-DAMAGED STRUCTURE (S08 OF 39022), 38th ST OVER I 94 NEAR KALAMAZOO

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STEEL EVALUATION OF VEHICLE-DAMAGED STRUCTURE (S08 OF 39022), 38th ST OVER I 94 NEAR KALAMAZOO

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Testing and Research Division
Research Project 75 TI-275
Research Report No. R-1029

Lansing, November 1976

The purpose of this investigation was to determine the physical properties of the steel in a beam that developed brittle fracture when struck by a vehicle.

On March 14, 1975 the bridge structure S08 of 39022, which carries 38th St over I 94 near Kalamazoo, was damaged by a truck trailer that was transporting two large fork-lift trucks. The truck was traveling in the westbound lane when a post on one of the fork-lifts struck several of the bridge beams. The fork-lift post extended to a height of slightly over 14 ft and the minimum underclearance of the bridge is posted as 13 ft - 11 in. The east fascia beam was struck first, apparently driving the fork-lift downward. The fork-lift then rebounded and the first interior beam received an impact on the east edge sufficient to fracture the beam in two and pull it from the structure onto the pavement below. Several other beams were hit by the fork-lift as the truck passed under the bridge but no other beams were fractured or dislodged from the structure. Figure 1a shows the east fascia beam that was hit, and Figure 1b shows the remaining fractured end of the first interior beam that was dislodged and the damage incurred by the second interior beam. Note that since there were no shear developers on the top of the beam it was free to pull loose from the bridge deck once the section at the diaphragm had completely fractured. In addition to the damage done to the beams, many of the connecting diaphragms in the span were twisted and many of the connecting bolts were sheared due to the large lateral loads that were transferred by the repeated impacts. The beam dislodged from the structure (Fig. 1a) was impacted on the edge of the flange at about mid-span. The fracture occurred at an intermediate diaphragm since it provided a fixation point against the lateral movement produced by the impact. The beam fractured at the south intermediate diaphragm but sheared loose from the north intermediate diaphragm. The beam also fractured at the point of impact, with the fracture running within 2 in. of the far edge of the flange and part way up the web (Fig. 2). No injuries were incurred in the accident, although one lane of I 94 was blocked by the beam until it could be removed.

The failure of this bridge beam occurred under an unusual and extreme impact loading. Normal loading on the bridge would not produce a fracture of this type and the mechanical properties of the beam were not suspected as being inadequate for the intended use. Our interest in studying the properties of the steel in the beam was due to the apparent brittle behavior of the steel at the points of fracture. The fascia beam and second interior beam both received a similar impact loading but they did not fracture like the first interior beam. Analysis of the fractured surface of the beam revealed that the crack originated at a rivet hole where the diaphragm con-

Figure 1a. East fascia of damaged span showing impact point of the fork-lift.

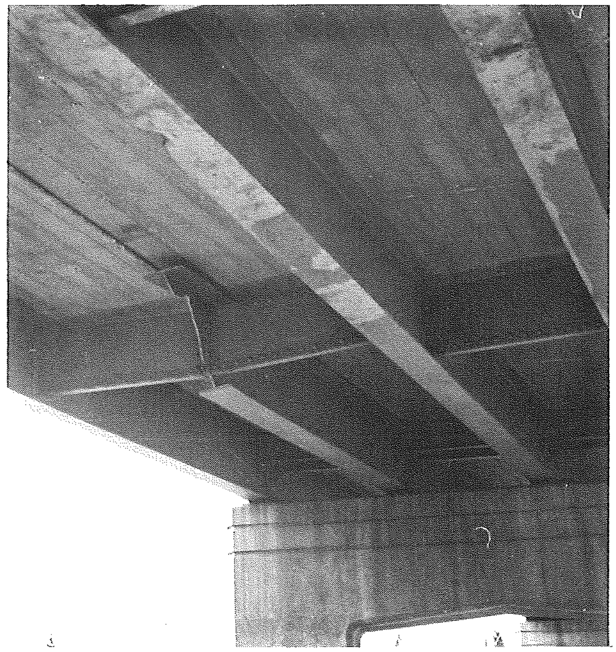


Figure 1b. First interior beam fractured at the connecting diaphragm and dislodged from bridge.

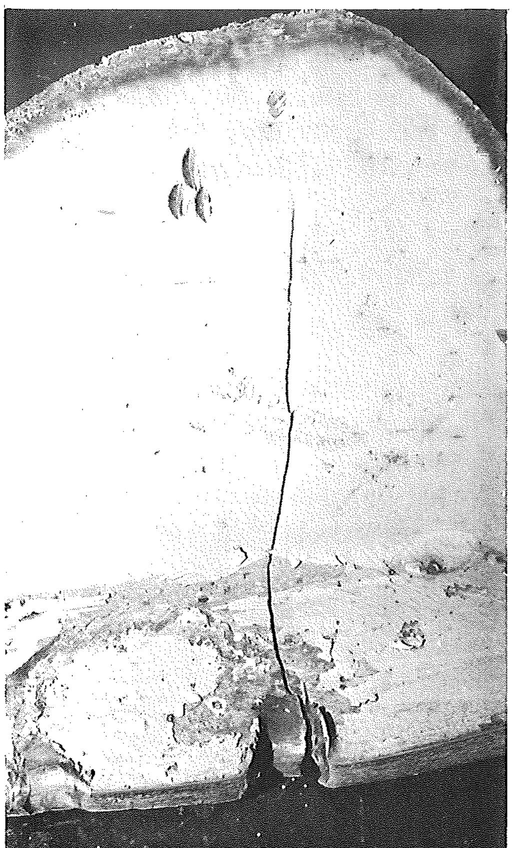
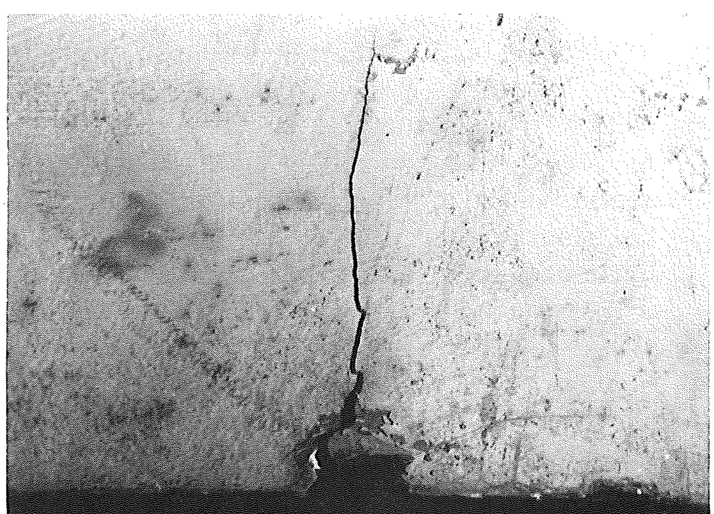


Figure 2a. Fracture at the point of impact on the first interior beam. Crack is shown running through the flange and part way up the web.

Figure 2b. Bottom side of the flange at the point of impact showing crack stopping before reaching far side of the flange.



nector angle attached to the web. This is evident in Figure 3 where the fractured web shows a "chevron pattern" (or V-pattern) of striations which is seen to point back to the edge of the rivet hole, thus depicting the origin of the crack. Figure 3 also shows a similar chevron pattern in the web on the other side of the same rivet hole which points back to the origin of the fracture on that section of the beam. There was no evidence of fatigue damage at the rivet hole, thus the fracture was totally initiated by the impact loading. Once the crack began propagating in both directions from the rivet hole, it ran completely through the top and bottom flanges of the beam, thus dislodging the beam from the structure. The fracture through the bottom flange and the upper portion of the web appeared to be predominantly brittle in mode and the fracture through the top flange was predominantly of a shear mode. The air temperature at the site was reportedly below 40 F at the time of the accident which could have contributed to the brittle behavior of the steel. An interesting feature of the fracture, as seen in Figure 4, was the sharp changes in the direction that the crack experienced as it traversed the web. At one location, shown in Figure 5a, the crack changed direction by nearly 90° at a location where the web was severely laminated. Figure 5b also shows multiple mid-plane laminations in the beam as revealed by the fractured surface. No particular significance can be attributed to the effect of the laminations on the crack propagation since the loading geometry during the failure is unknown and obviously included some twisting as the beam was torn free. A shift in the loading direction during failure could have contributed significantly to the changes in crack direction noted. The section of the fractured beam that remains in the structure is supposed to be sent to the Research Laboratory after it has been removed from the bridge. We plan to conduct ultrasonic tests on the web of this beam to define the extent of lamination in the beam.

The beams in the damaged span of the bridge were W30 x 124, which have a nominal depth of 30 in., a flange size of 15/16 x 10-1/2 in. and a web thickness of 5/8 in. A chemical analysis of the steel yielded the following percentages by weight: 0.32 carbon, 0.71 manganese, 0.05 silicon, 0.015 phosphorous, 0.029 sulfur and 0.05 copper. This conforms to the chemical requirements of ASTM A7 steel which only limits phosphorous and sulfur content. The carbon content of the steel is quite high. This high carbon content will contribute to a low fracture toughness. The ASTM A36 steel specification limits carbon to a maximum of 0.30 on a check analysis. The bridge under investigation was constructed around 1950, however, which is prior to the advent of A36 steel. Tensile tests were conducted on the top and bottom flanges of the beam to characterize its strength properties. The results of these tests are shown in Table 1. ASTM standard round specimens (0.505 in. diameter), were used in the tensile tests and

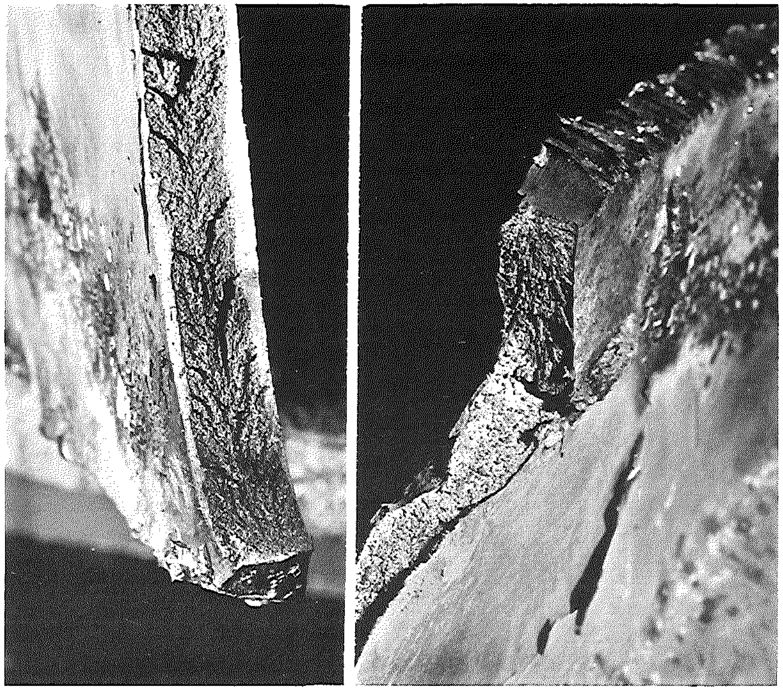


Figure 3. Chevron patterns in beam web pointing to the rivet hole as the fracture origin. Upper portion (left) and lower portion (right).

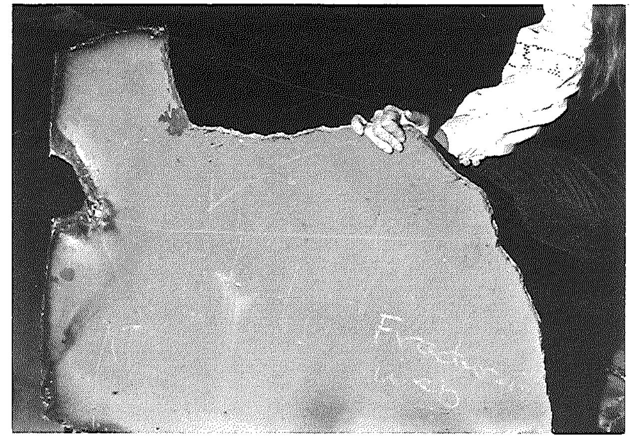


Figure 4. Irregular crack propagation path in the beam web (web plate is oriented up in picture as in the beam).

Figure 5a. Nearly 90° change in the direction of crack propagation in beam web at an area of midplane lamination.

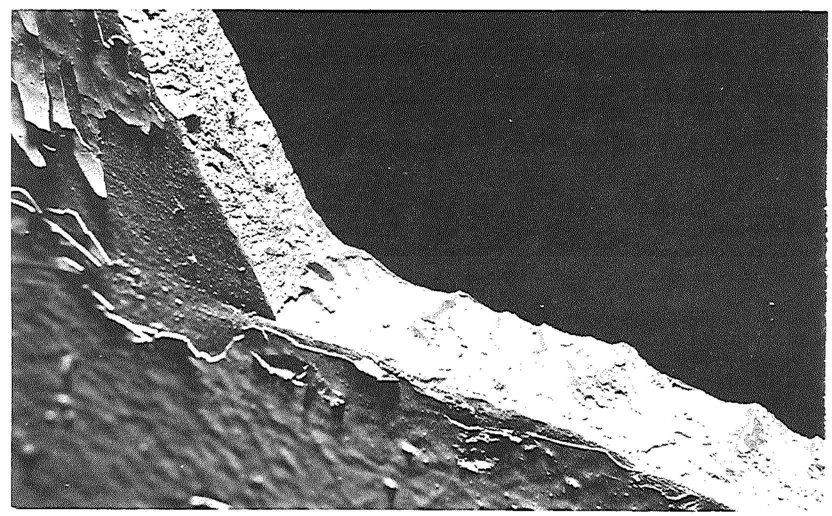
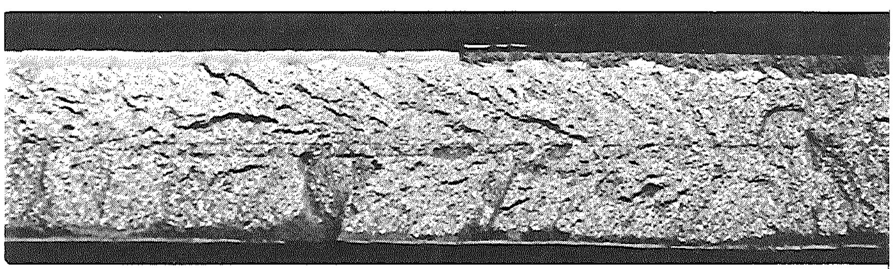


Figure 5b. Multiple laminations visible in beam web on the fractured surface.



the specimens were removed longitudinally from the flanges starting from the flange tip (specimen 1) and progressing to the web/flange junction (specimen 5).

TABLE 1
TENSILE PROPERTIES OF STEEL TAKEN FROM THE FRACTURED BEAM
(Specimens are numbered 1 to 5 starting at flange tip and ending at the web/flange junction.)

Specimen No.	Yield Strength,[1] psi	Tensile Strength, psi	Elongation,[2] percent	Reduction of Area, percent
TF-1[3]	47,400	73,900	37	57
TF-2	45,300	73,800	39	56
TF-3	43,000	74,000	38	57
TF-4	33,700	75,400	39	54
TF-5	32,000	74,700	36	55
BF-1[3]	41,200	72,400	38	58
BF-2	41,300	73,900	37	57
BF-3	41,200	73,900	38	55
BF-4	40,200	74,100	38	56
BF-5	33,300	74,200	36	55

[1] Yield strength taken as the stress at the "sharp kneed" yield point on the stress-strain curve or the 0.2 percent offset if no sharp yield was present.

[2] 2-in. gage length

[3] TF denotes specimen from top beam flange. BF denotes specimen from bottom beam flange.

Table 1 reveals a significant decrease in the yield strength of the steel from the flange tip to the web/flange junction (32 percent in top flange and 19 percent in bottom flange). The other tensile properties are fairly uniform across the section. Such a variation in yield strength is common in rolled shapes such as this beam and can be attributed to the difference in plastic deformation experienced in the rolling process and to the different rates of cooling that occur in the beam. The flange tip and web receive the most plastic work during the rolling process and the web/flange junction

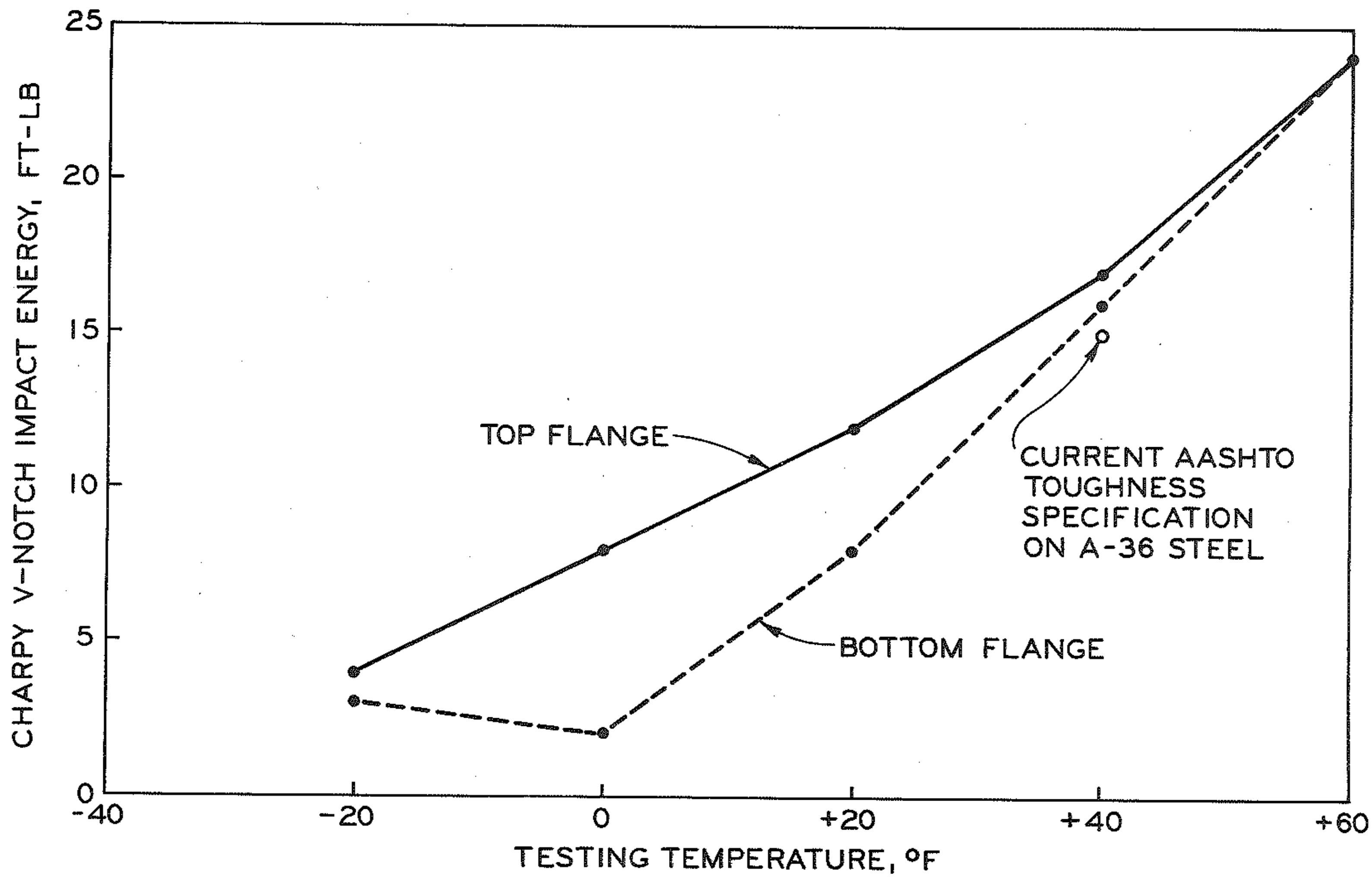


Figure 6. Energy transition-temperature curves for the top and bottom flanges of the fractured beam.

receives the least. The flange legs and web also cool faster than their junction, which results in a finer grain structure and a corresponding higher yield strength.

The yield strength commonly reported for a rolled I-beam is measured from a specimen taken from an unspecified location in the beam web. Our experience has shown that yield strength in the web is usually equal to or greater than that measured at the flange tip. This is understandable because of the work involved in reducing the web thickness and the rapid cooling experienced by the thin web section. Thus, the specimens TF-1 and BF-1 would closely represent the ASTM specified tensile properties and easily meet the minimum requirements of either A7 or A36 steel.

Note that as measured by the 'static' tensile properties of 'elongation' and 'reduction of area,' the steel would be considered to possess high ductility. It will next be shown that this high ductility does not correspond to a high fracture toughness in this beam. Standard Charpy V-notch impact tests were run on steel taken from the top and bottom flanges of the beam. At a test temperature of +40 F sets of three specimens each were tested. The top flange had an average impact energy of 17 ft-lb and the bottom flange an average of 16 ft-lb. When this bridge was constructed there were no specifications covering the impact energy of bridge steels. Recently we have adopted the AASHTO Toughness Specification which would call for a minimum acceptance level of 15 ft-lb at +40 F for a beam of this type made of A36 steel. Hence the beam tested would meet this minimum requirement. It is interesting to note the energy temperature transition that occurred in this beam as sets of three specimens each were tested at decreasing temperatures down to -20 F (Fig. 6). The bottom flange is seen to develop a low of only 2 ft-lb at 0 F which would indeed predict a brittle behavior at this temperature under a high loading rate. The top flange developed 7 ft-lb at 0 F which would indicate a slightly higher resistance to brittle behavior than the bottom flange. Such a difference in the mode of fracture was evident in the top and bottom flanges, but this may have been due to a shift in the loading geometry during fracture. The temperature of the beam at the time of the accident was reported as below 40 F and possibly below the freezing point. A case in point here is that the specification of a minimum toughness level at a specified temperature (e.g., 15 ft-lb at 40 F) does not preclude brittle behavior at a lower temperature if the steel undergoes a rapid energy transition below the specified acceptance test temperature. (The rate of loading also is a very important consideration here.) This problem is currently receiving considerable attention in the field of structural steel fracture toughness research. The current method of specifying toughness for structural steel may prove to be inadequate in the future, but currently it is serving the function of rejecting heats of steel that exhibit extremely low toughness. We are quite sure that some of our existing structures contain such brittle steels.

Conclusions

The fracture experienced by this beam was initiated by a severe and unusual, concentrated impact loading, applied by a traveling fork-lift column. The properties of the beam, even though they were unusual, cannot be deemed as inadequate for the intended loading. However, the observed fracture behavior of the beam as related to the measured properties has graphically demonstrated the fact that brittle fractures can occur in so-called ductile materials, and this study has been helpful in our attempt to understand such phenomena.

The steel in the beam that fractured and was dislodged from the damaged bridge was seen to meet all of the ASTM requirements for A7 steel that existed at the time the structure was built. Further, Charpy impact testing of the steel in the top and bottom flanges revealed that they both exceed the current AASHTO toughness requirement on A36 steel of 15 ft-lb at 40 F, Charpy V-notch impact energy. Lowering the impact test temperature indicated a rapid decrease in the corresponding toughness of the bottom flange and not as severe a decrease in the top flange. This transitional behavior undoubtably contributed to the different fracture modes observed in the two flanges.