BRITTLENESS OF REINFORCED CONCRETE STRUCTURES UNDER ARCTIC CONDITIONS

Lauri Kivekäs, Research Scientist
Technical Research Centre of Finland (VTT)
Concrete and Silicate Laboratory (BET)

Charles J. Korhonen, Research Civil Engineer
US Army Corps of Engineers (USACE)
Cold Regions Research and Engineering Laboratory (CRREL)

ABSTRACT

The behaviour of reinforced and unreinforced concrete beams was studied under impact load at low temperatures, and the results were compared with the behaviour of reinforcing steel in the Charpy-V impact tests. Transition temperatures as high as -30 °C were obtained in the Charpy-V test whereas at temperatures as low as -63 °C no brittle failure occurred in the concrete beams, even in those beams where the rebars were intentionally notched. The impact strength of unreinforced concrete increased considerably at lower temperatures.

Key words: Reinforced concrete, brittleness, arctic.

1. INTRODUCTION

At sufficiently low temperatures the failure of steel becomes brittle, signifying loss of ductility. This is accompanied by a sharp decrease in impact strength. Owing to an increase in construction activities in arctic regions, there is some concern about the possibility of embrittlement of reinforced concrete structures at the very low ambient temperatures which exist in these areas.

Cold brittleness of reinforced concrete structures can be studied either by testing entire structures or by testing concrete and reinforcing steel separately and estimating the behaviour of an entire structure from the individual behaviour of the components. The temperature at which the failure of steel becomes brittle is called the transition temperature. It is not a constant for any type of steel, depending on the rate of loading, the size and shape of the specimen and the presence or absence of notches.

The availability of research data is abundant /1, 2, 4/ concerning the performance of steels under slow loading. Reinforcing steels retain good ductility in the +20 to -80 °C temperature range. As the temperature is lowered, the yield strength increases a little more rapidly than the tensile strength, but even at -80 °C steels yield well before they fail. Elongation and reduction in area decrease a little, but are still considerable at -80 °C.

Under rapid impact load, brittle failure occurs at much higher temperatures than under slow loading. Usually the impact strength of steel is tested using a notched bar impact bend test, such as the Charpy-V test.

In this test, a specimen machined into prismatic shape with a notch in the tensile zone is loaded to failure with a very rapid transverse impact load. However, the test was developed for testing structural steel and is not considered suitable for testing reinforcing steels, which are subjected only to axial loads in concrete structures. The loading rate in the Charpy test is much higher than the actual highest loading rates of reinforcing steels in concrete structures under impact load /2/. Furthermore the shape of the test specimens differs from the shape of reinforcing bars and it is highly unlikely that sharp notches are present in reinforcing steels.

However, since the notched bar impact bend test is a standardized test method (ASTM A 370) it has been used for testing the impact strength of reinforcing steels and there is no research data available from more suitable types of tests. In Charpy-V tests the transition temperature of reinforcing steels has been reported to occur from +20 to -20 °C /1, 2/. These results are of little use when judging the brittle failure of reinforced concrete structures in arctic regions; they are suitable only for comparing the behaviour of one steel to another.

The impact strength of unreinforced concrete increases at low temperatures. In tests /3/ where notched concrete prisms were loaded with Charpy's hammer, the impact strength at -45 °C was found to be 50 % higher than at +20 °C.

No research data exists on impact tests with reinforced concrete structures at low temperatures. In order to study this, a joint test programme was carried out in 1984 by BET and CRREL. The purpose was to determine whether concrete elements failed in a brittle manner when subjected to low temperatures and impact loads normally received during transportation and erection in arctic regions. The purpose was also to compare the low temperature impact behaviour of the reinforced beams to reinforcing steels in the Charpy-V test.

2. TESTS

Impact strengths of concrete beams and individual lengths of reinforcing steels (rebars) were tested at temperatures ranging from +20 to -63 °C. The concrete beams were tested in bending by a falling weight, while the rebars were tested using the Charpy-V notched bar impact bend test.

2.1 Test specimens

A total of 45 concrete beams measuring 150 mm x 300 mm x 1500 mm were fabricated for the tests. Of the beams 36 were reinforced according to Fig. 1 and 9 were unreinforced. Two types of tension reinforcement were used: hot rolled deformed and cold worked smooth bars. Notches are unlikely to exist in reinforcing steels. However, in the presence of notches the transition temperature of the steel may be higher due to the biaxial stress state in their vicinity. In order to study this effect some of the beams were reinforced with tension steels having a 1 to 2 mm deep and approximately 5 mm wide u-notch on the under-side at the midspan of the beam.

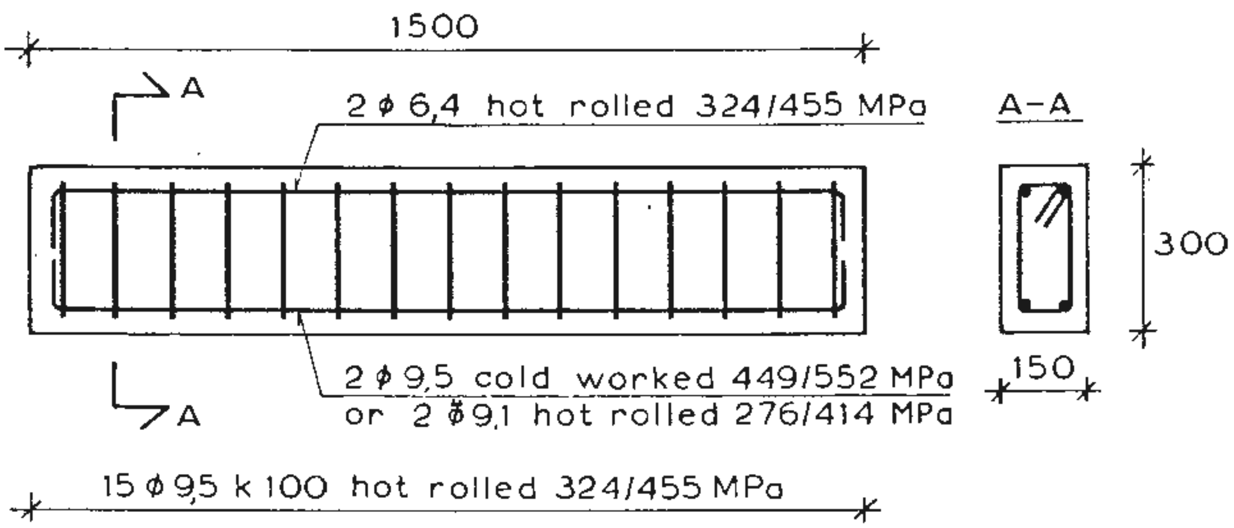


Fig. 1. Beam reinforcement pattern.

The beams were distributed according to their tension reinforcement into five groups as depicted in Table 1. Table 1 also shows the different temperature ranges used during testing.

Table 1. Tension steel bars and testing temperatures.

Type of tension bars	Beam markings	Testing temperatures (°C)
Hot rolled deformed bars without notches	A1, A2, A3 A4, A5, A6 A7, A8 A9	+20 -23...-26 -35...-38 -50
Cold worked smooth bars without notches	B1, B2, B3 B4, B5, B6 B7, B8 B9	+20 -25...-27 -35...-36 -63
Hot rolled deformed bars with notches	C1, C2, C3 C4, C5, C6 C7, C8 C9	+20 -24...-27 -30...-32 -53
Cold worked smooth bars with notches	D1, D2, D3 D4, D5, D6 D7, D8 D9	+20 -27 -34...-35 -54
Unreinforced beams	T1, T2, T3 T4, T5, T6 T7, T8	+20 -27...-28 -42...-44

For the impact tests of individual rebars ten specimens were machined from both types of bar. The shape of these specimens differed from the standard Charpy-V test specimens. The original shape of the reinforcing bars was otherwise preserved, but the under-surface was machined flat in order for the test specimens to rest firmly on the supports. The depth of the V-notch was 1.5 mm, whereas the standard notch is 2 mm deep.

The concrete for the beams was made from high early strength Portland cement. The compressive strength of the concrete was tested using standard cylinders at the age of two months and was found to range from 20 to 28 MPa.

The steels used in the tests were produced in the United States. Their compositions are shown in Table 2.

2.2 Test methods

The beams were simply supported. The loading device used was a falling weight deflectometer in which a weight of 50 to 300 kg can be dropped from a height of 30 to 400 mm. According to the manufacturer's literature this imparts a 28-ms pulsed load of 7 to 105 kN to a steel plate resting at the midspan of the beam. The plate measured 100 x 150 mm^2.

Table 2. Steel composition. CW = cold worked smooth bar
HR = hot rolled deformed bar

Steel	Composition (%)																
	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Al	W	V	Ti	Co	Sn	As	O	N
CW	0.19	0.30	0.84	0.042	0.011	0.03	0.09	0.02	0.20	0.03	0.00	0.01	0.00	0.02	0.02	0.03	0.003	0.005
HR	0.34	0.24	0.70	0.043	0.015	0.10	0.11	0.02	0.33	0.01	0.01	0.01	0.00	0.01	0.02	0.02	0.010	0.009

All the beams were loaded at room temperature. Prior to loading the beams were cooled in a cold room to the desired test temperature and subsequently moved to the loading room where loading was conducted as quickly as possible. The temperature of the cold room was kept constant at -30 ^{o}C; this was the same temperature as for beams 4, 5 and 6 of each group shown in Table 1 at the time of removal for loading. In order to reach lower temperatures an insulated box cooled with liquid nitrogen was built inside the cold room and beams 7, 8 and 9 of each test group (Table 1) were cooled within the box to their test temperatures. The temperature rise in the tension steels during loading was monitored using thermocouples.

The beams were approximately one month old at the start of the tests, which lasted 5 weeks. Testing was performed by repeatedly dropping increasing loads until the maximum loading capacity of the falling weight deflectometer was reached. Subsequently the dropping was repeated at maximum load until the rebars broke. Load levels used with the reinforced beams are shown in Table 3 along with their corresponding energy and load impulse range. With unreinforced beams the levels varied with temperature but beams T7 and T8 were loaded with the same levels used for the reinforced beams.

During each drop the peak value of the load impulse was measured automatically by the falling weight deflectometer. Following each drop the permanent deflection and maximum crack width were measured.

Table 3. Load levels used in the loading of all reinforced beams and unreinforced beams 7 and 8.

Drop no.	Load level Mass/height (kg/mm)	Energy (Nm)	Peak value of the load impulse (kN)
1	100/30	29	10...16
2	100/180	177	18...29
3	200/90	177	28...41
4	200/120	235	34...46
5	200/240	471	47...60
6	300/240	706	54...74
7	300/360	1059	62...87
≥8	300/360	1059	48...87

Impact testing of the rebars was accomplished using the Charpy-V test according to Finnish standard SFS 2853 /5/, which is quite similar to ASTM A-370. The tests were carried out at ten different temperatures from +40 to -70 °C, one test bar of each steel type at each temperature.

3. RESULTS

Since each cooled beam gradually warmed up during testing, at low temperatures the temperature of the tension steels at the onset of cracking of the concrete has been chosen as the test temperature. The first permanent deflection of each beam occurred simultaneously, indicating that the steels had yielded and that the beam was ductile.

None of the beams broke in a brittle manner; the steels yielded, the concrete cracked and the beams deflected considerably before failing. For this reason no transition temperatures were noted. For these tests it is safe to assume that beam transition temperatures are lower than the -50 to -63 °C test temperature range.

3.1 Impact strength of beams

The number of drops needed to break the tension steel of the beams varied greatly even between similar beams loaded at the same temperature. This may partly be due to the differing amount of cracks. However, no reinforced beam failed before the maximum loading capacity of the falling weight deflectometer was reached. The failure load was thus the same for all reinforced beams and differences occurred only in the number of drops at maximum load. As can be seen from Fig. 2, the impact strength was not affected by temperature.

Impact strength of the unreinforced beams increased considerably at low temperatures (Fig. 3). At -43 °C the increase, compared with that at +20 °C, was about 120 %, which was clearly higher than the 50 % increase for notched concrete prisms reported in reference /3/. Furthermore, at - 43 °C the impact strength was almost that of the reinforced beams. Beam T7 failed one drop prior to the maximum loading capacity of the falling weight deflectometer and beam T8 only on the first drop at maximum load, which was the same as for failure of some reinforced beams.

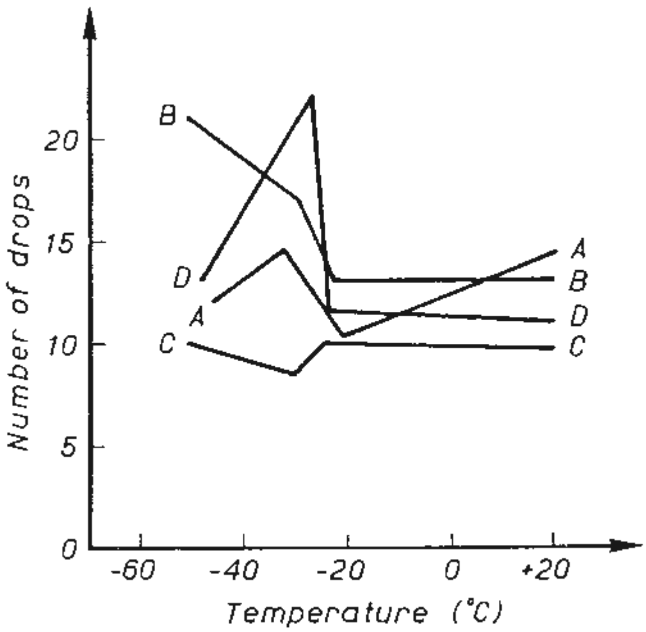


Fig. 2. Number of drops required to break the tension steel of beams.

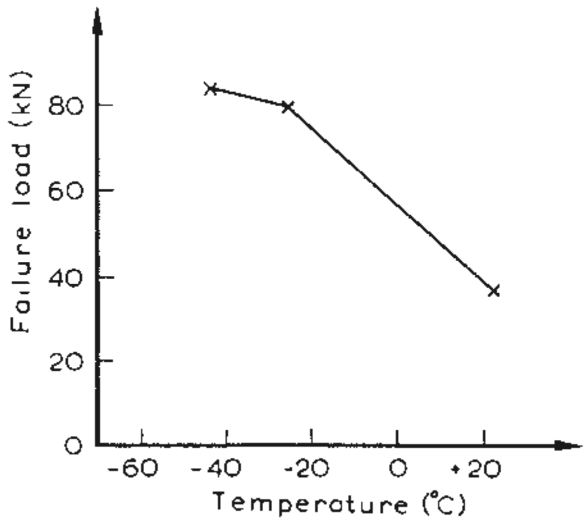


Fig. 3. Impact strength of unreinforced beams.

Owing to the increased impact strength of concrete, the load required for the first occurrence of cracks in reinforced beams also increased considerably at low temperatures, as shown in Fig. 4. This was accompanied by a decrease in the number of cracks. The cracks usually occurred near the stirrups as the area of concrete in these cross-sections was the smallest. Had there been no stirrups in the middle part of the beams the load required for occurrence of the first cracks might have been somewhat higher.

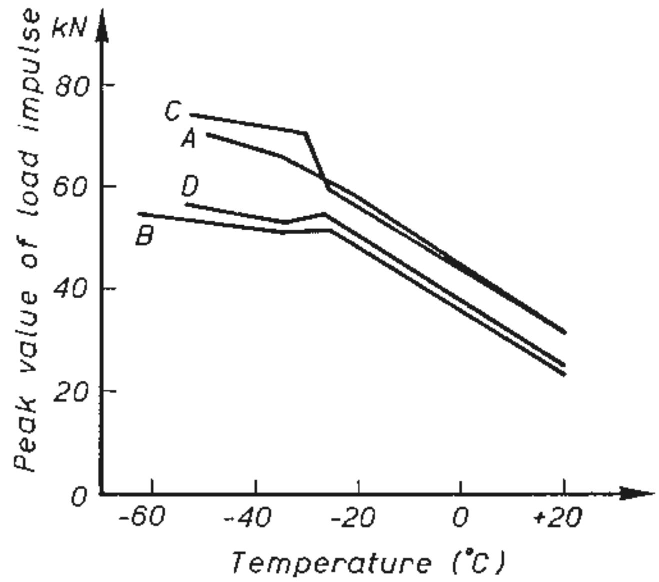


Fig. 4. Load required for occurrence of the first cracks in reinforced beams.

3.2 Ductility of beams

There is a fair amount of variation in the permanent deflection values of the beams, the maximum crack width of concrete and in the reduction in area of the steels. However, it can be said that the ductility of the beams did not change significantly at low temperatures.

In Fig. 5 the permanent deflections indicate that the ductility of the beams reinforced with hot rolled deformed bars decreased at low temperatures, but still remained considerable. This was confirmed by a reduction in crack width, but on the other hand the values of reduction in area of the steels (Fig. 6) increased at the same time.

Ductility of the beams reinforced with cold worked smooth bars even increased in some cases at low temperatures. The reduction in area decreased with notched bars and remained unaltered with unnotched bars.

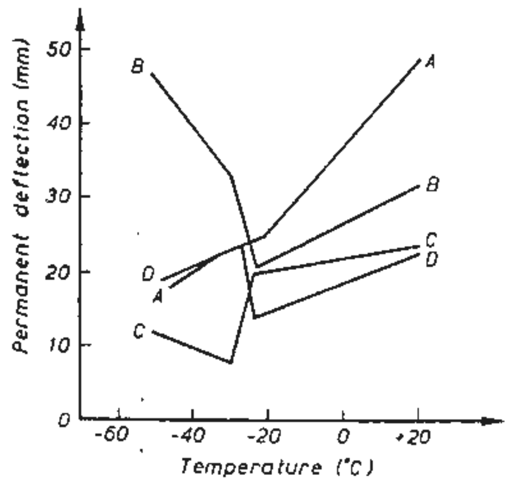


Fig. 5. Permanent deflections of reinforced beams prior to failure of the steels.

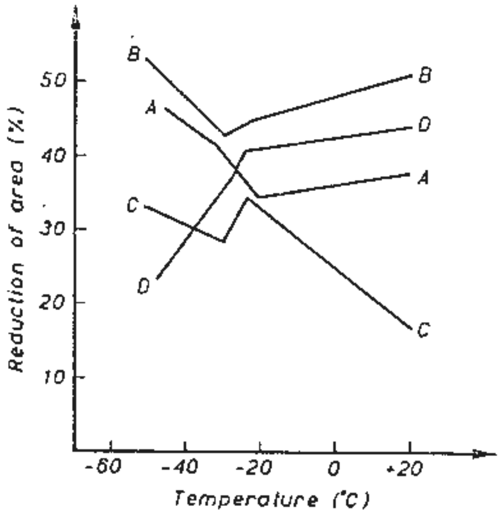
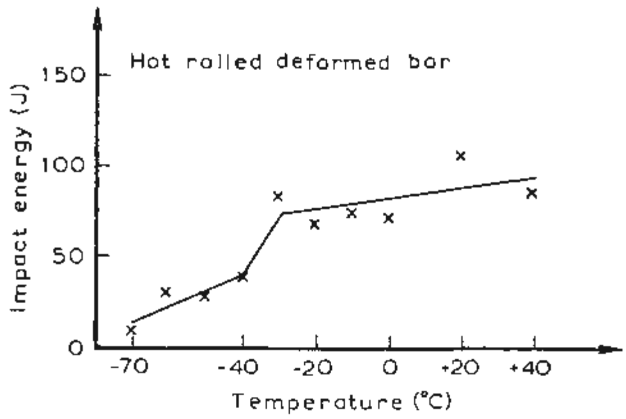


Fig. 6. Reduction in area of tension steels following their failure in the beams.

3.3 Impact tests on plain rebars

In the Charpy-V test the transition temperature of the hot rolled deformed bar was -30 to -40 °C and that of the cold worked smooth bar -50 to -55 °C. The dependence between failure energy and temperature is shown in Fig. 7 for both steel types. These transition temperatures are higher than the lowest test temperatures for the beams. Since there was no brittleness of the beams even at these lower test temperatures, it appears that the Charpy-V test gives higher transition temperatures than rebars actually have within concrete structures. The beams with notched and unnotched hot rolled deformed rebars retained their full impact strength at -53 °C and -51 °C respectively, whereas in the Charpy-V test at the same temperatures the rebars only retained approximately 30 % of their room temperature impact strength. At -63 °C, which was the lowest test temperature of the beams reinforced with cold worked smooth bars without notches, the impact strength of the bars in the Charpy-V test was only about 15 % of the room temperature value, whereas the beam retained its full impact strength. The lowest test temperature (-52 °C) of the beams reinforced with cold worked smooth bars with notches was about the same as the transition temperature of these rebars in the Charpy-V test. In comparison to other tests, the transition temperatures in our Charpy-V test are lower than the values +20 to -20 °C given in references /1, 2/. This may be due to the non-standard shape of the test specimens, but may also be due to the composition of the steels.



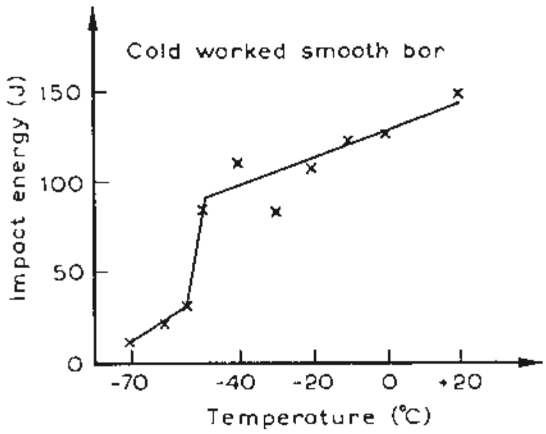


Fig. 7. Relationship between failure energy of the steels and temperature in the Charpy-V test.

4. CONCLUSIONS AND SUMMARY

- Under impact load reinforced concrete structures usually become brittle at considerably lower temperatures than reinforcing steels in the Charpy-V notched bar impact bend test. In this study the beams reinforced with hot rolled deformed bars retained full impact strength even at -53 °C, whereas in the Charpy-V test the steels already became brittle at -30 to -40 °C. When testing cold brittleness of reinforcing steels, their actual loading inside concrete structures must be simulated as closely as possible, since the manner of loading significantly affects the transition temperature. The Charpy-V test is not suitable for determining the transition temperature of reinforcing steels, although it may be used in the comparison of impact behaviour of reinforcing steels with different compositions.

- It is improbable that reinforced concrete elements would break in a brittle manner in arctic regions under normal impact loads occurring during their transportation and erection. In the tests no beams broke in brittle fashion even though the impact load used was at least as severe as these loads. All beams retained full impact strength and there was no significant loss in ductility. The lowest test temperatures for different beam groups measured -50 to -63 °C. Even notching the reinforcing steels did not cause brittle failure of the beams.

- Impact strength of unreinforced concrete increases considerably at low temperatures. This reduces cracking in reinforced concrete structures. Furthermore, it has a significant effect on the safety of lightly reinforced concrete structures. At low temperatures the ratio of the impact strength of concrete to the impact strength of the reinforced structure increases, and if the temperature falls sufficiently for the steels to become brittle, the relative impact strength of the structure still remains considerable. In the tests the percentage of the reinforcement was 0.3 and the above-mentioned ratio increased to well over 50 % at the lowest test temperatures. However, if the percentage of reinforcement is much higher, the increased impact strength of concrete will not add much to the safety of the structure in the case where the steels become brittle.

- The results obtained apply only to the steel types and loading used in the tests. The composition of the steel, particularly its carbon content and grain size, significantly affects its cold embrittlement. Upon study of the impact behaviour of structures reinforced with other types of steel, conclusions can be drawn from the results of this study by testing only the Charpy-V transition temperature of the steel and comparing this to the values obtained in the study. In order to widen the range of steels for comparison, some additional impact tests on beams reinforced with steels having a higher Charpy-V transition temperature than in this test would be needed.

  Since the loading rate also has a significant effect on the transition temperature, the results of this study do not apply if the loading rate is much different from that in the tests.

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