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ON BIAS IN T_o VALUES DERIVED WITH COMPACT AND PCVN SPECIMENS

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ABSTRACT

The Heavy-Section Steel Irradiation (HSSI) Program at Oak Ridge National Laboratory (ORNL) includes a task to investigate the bias in the reference fracture toughness transition temperature values, T_o, derived with the pre-cracked Charpy (PCVN) and compact specimens. The PCVN specimen, as well as any other fracture toughness specimen that can be made out of the broken Charpy specimens, may have exceptional utility for the evaluation of RPV steels. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs. Precracking and testing of Charpy surveillance specimens would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. However, there is a growing number of indications that there might be a bias in T_o values derived from PCVN and compact specimens. The present paper summarizes data from the series of experiments that use subsize specimens for evaluation of the transition fracture toughness of reactor pressure vessel (RPV) steels conducted within the HSSI Program. Two types of compact specimens and three types of three-point bend specimens from five RPV materials were used in these subsize experiments. The current results showed that T_o determined from PCVN specimens with width (W) to thickness (B) ratio W/B=1, on average, are lower than T_o determined from compact specimens with W/B=2. At the same time, three-point bend specimens with W/B=2 exhibited T_o values that were very similar to T_o values derived from compact specimens.

Keywords: fracture toughness, pressure vessel, T_o, PCVN, subsize specimens.

INTRODUCTION

The Heavy-Section Steel Irradiation (HSSI) Program at Oak Ridge National Laboratory (ORNL) includes a task to investigate the bias in the reference fracture toughness transition temperature values, T_o, derived with the pre-cracked Charpy (PCVN) and compact specimens. The PCVN specimen, as well as any other fracture toughness specimen that can be made out of the broken Charpy specimens, may have exceptional utility for the evaluation of RPV steels. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs. Precracking and testing of Charpy surveillance specimens would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. However, there is a growing number of indications that there might be a bias in T_o values derived from PCVN and compact specimens. The present paper summarizes data from the series of experiments that use subsize specimens for evaluation of the transition fracture toughness of reactor pressure vessel (RPV) steels conducted within the HSSI Program. The testing was performed under carefully controlled conditions in accordance with ASTM E1921 such that the values could be used to predict the fracture toughness performance of large specimens.

MATERIALS AND SPECIMENS

Two types of compact specimens [C(T)] and three types of three-point bend specimens were used in these subsize specimen experiments. Compact specimens were 0.4T and 0.2T. Three-point bend specimens were standard Charpy-size (10x10x55 mm), 5x5x27.5 mm, and 5x10x55 mm type specimens. However, the main focus of the testing was on the use of PCVN specimens. Other specimens were used as an additional source for studying the potential use of specimens even smaller than PCVN, as well as examining compatibility of fracture toughness values derived from compact and three-point bend specimens.

Five materials were used in this study. An ASTM A533 grade B class 1 plate, designated HSST Plate 02, was selected for the present study. The selection of this plate was based on the existence of an extensive fracture toughness data base for Plate 02 accumulated by testing large specimens. Seventy specimens of different sizes up to 11T thickness were tested by Westinghouse for establishment of what is now known as the ASME lower-bound K_{Ic} curve [1]. Additionally, 25 1T compact specimens of the plate were subsequently tested in the transition range as a part of the Heavy-Section Steel Technology Program (HSST) performed at ORNL [2]. Another ASTM A533 grade B class 1 plate is the IAEA correlation monitor material, plate JRQ, which is also well characterized within the international community. A third ASTM A533 grade B class 1 plate is HSST Plate 13. Fracture toughness of this plate has been extensively characterized within the HSST program by ORNL [3]. Two other plates are ASTM Modified A302 grade B plates (plate codes Z2 and Z7) from a ductile fracture toughness characterization study [4] performed within the HSST program by ORNL. Table 1 provides a summary of materials and specimen types used in this study.

Table 1. Matrix of materials and specimens types used in this study.

Material	PCVN	5x10x55mm	5x5x27.5mm	0.4T C(T)	0.2T C(T)	1T C(T)
HSST Plate 02	14	18	12	6	6	-
A533B Plate JRQ	20	6	6	8	7	-
HSST Plate 13	6	-	-	-	-	-
Mod. A302B, Z2	6	-	-	-	-	6
Mod. A302B, Z7	6	-	-	-	-	6

FRACTURE TOUGHNESS RESULTS

Specimens were fabricated, precracked, and tested in accordance with ASTM E1921-02 [5]. An outboard clip gage was used to measure load-line displacement on C(T) specimens and an LVDT transducer was used to measure load-line displacement on PCVN specimens. The unloading compliance method was used to obtain J-integral versus crack extension data. From J-integral versus crack extension data, a J-integral at the point of cleavage instability, J_c, was determined and a critical value of stress intensity, K_{Jc}, was calculated from:

$$K_{Jc} = \sqrt{J_c \frac{E}{1 - \nu^2}}\,, \tag{1}$$

where E is Young's modulus and v=0.3 is Poisson's ratio. In the present work, the following fit to the data from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code was used for temperature dependence of Young's modulus:

$$E = 192520 - 66 \cdot T\,, \quad in\ MPa\ when\ T\ is\ in\ {}^{o}C \tag{2}$$

For comparison purposes, all K_{Jc} data were converted to their 1T equivalence using the size-adjustment equation from E1921 [5]:

$$K_{Jc}(1T) = 20 + \left[K_{Jc(x)} - 20\right]\left(\frac{B_x}{B_{1T}}\right)^{1/4} \tag{3}$$

where $K_{Jc\,(x)}$ = measured K_{Jc} value,
B_x = gross thickness of test specimen,
B_{1T} = gross thickness of 1T C(T) specimen.

Attempts were made to test at least six specimens at a given temperature. That would allow determining the median fracture toughness as follows [5]:

$$K_{Jc(med)} = 20 + \left[\ln(2) \cdot \sum_{i=1}^{N} \frac{\left(K_{Jc(i)} - 20\right)^4}{r}\right]^{1/4} \tag{4}$$

where $K_{Jc(i)}$ = either a valid K_{Jc} datum or dummy substitute ($K_{Jc\,(limit)}$) for invalid datum (see definition of invalid data below),
r = number of valid data,
N = number of data (valid and invalid).

A K_{Jc} datum is considered invalid if it exceeds the $K_{Jc(limit)}$ requirement of E 1921 [5]:

$$K_{Jc(\mathrm{limit})} = \sqrt{\frac{b_o\,\sigma_{YS}}{30} \cdot \frac{E}{1 - \nu^2}} \tag{5}$$

where b_o is the specimen remaining ligament and σ_{YS} is the material yield strength.

Specimens of HSST Plate 02 were machined in the T-L orientation and tested at two temperatures, -30°C and -50°C. Specimens of the JRQ plate were machined in the T-L orientation and tested at -100°C. Precracked Charpy specimens were machined from the ¼ - and ¾ - thickness locations of this plate and tested as part of an International Atomic Energy Agency (IAEA) round-robin. Precracked Charpy specimens of HSST Plate 13 were machined from broken halves of 2TC(T) specimens that were tested in a previous HSST study [3]. The test temperature was selected to be -75°C to match the large number of 0.5T C(T), 1T C(T), 2T C(T), and 4T C(T) specimens tested at the same temperature in Ref. [3]. Table 2 provides a summary of results from the previous study [3]. All compact specimens of Plate 13 tested at -75°C in Ref. [3] generated valid K_{Jc} values. Analyzed together, they yielded $K_{Jc\,(med)}$(1T) = 111.33 MPa / m and T_o= -83°C. Precracked Charpy specimens of Modified A302B plates Z2 and Z7 were tested at -80°C. This temperature was selected based on Charpy transition temperatures reported for both plates in Ref. [4].

Table 2. Summary of C(T) specimen fracture toughness data of HSST Plate 13 tested at -75°C in Ref. [3]

Specimen size	0.5T C(T)	1T C(T)	2T C(T)	4T C(T)
Number of specimens tested	20	26	12	6
$K_{Jc(med)}$, MPa / m	123.19	110.58	102.14	86.72

Test results from the current study are summarized in Table 3.

Table 3. Fracture toughness data of all materials and specimens employed in this study.

Material	Test T, °C	Specimen Type	N/r	$K_{Jc\,(med)}$, MPa$\sqrt{m}$	T_o, °C
HSST Plate 02	-30	10x10x55mm	7/5	121.27	N/A
		5x10x55mm	10/8	112.52	-14.2
	-50	10x10x55mm	7/7	88.98	-26.6
		5x10x55mm	8/8	75.69	-0.3
		5x5x27.5mm	12/6	97.03	N/A
		0.4T C(T)	6/6	75.79	-12.6
		0.2T C(T)	6/6	74.5	1.3
A533B Plate JRQ	-100	10x10x55mm	20/20	88.76	-76.4
		5x10x55mm	6/6	98.76	-73.9
		5x5x27.5mm	6/4	84.56	N/A
		0.4T C(T)	8/8	79.37	-66.8
		0.2T C(T)	7/7	97.66	-73.0
HSST Plate 13	-75	10x10x55mm	6/1	187.19	N/A
Mod. A302B, Z2	-80	10x10x55mm	6/4	114.62	N/A
		1T C(T)	6/6	79.87	-62.2
Mod. A302B, Z7	-80	10x10x55mm	6/2	153.16	N/A
		1T C(T)	6/2	123.17	-95.0

DISCUSSION

Since acceptance of ASTM E1921 in 1997, the master curve methodology has received a significant increase in the amount of attention for application to RPV materials. There are several key items that made this methodology very attractive. One is the ability to determine the entire transition fracture toughness curve with tolerance bounds of a RPV material by testing only several PCVN (or even smaller) specimens. However, very soon after approval of E1921, some researchers reported a bias in PCVN-generated T_o values to be lower than from compact specimens, see Refs. [6-8]. Those earlier findings are illustrated in Figure 1 from Ref. [6] where PCVN- and C(T)-generated T_o values available at that time are compared.

These initial observations were later supported by well controlled single-variable experiments at UCSB [9] and statistical analysis of this bias by Wallin [10]. Moreover, ASTM Sub-Committee E08.08 organized a workshop on Applications and User's Experience with the E1921 Standard in November 2002. There were several presentations, both analytical and experimental, showing that there was a difference in T_o values derived from compact and PCVN specimens. The consensus of this workshop was that the difference is between 3-point bend and compact specimens in general, not only between PCVN and C(T). However, Petti and Dodds [11] analytically concluded that 3-point bend specimens with a standard width (W)-to-thickness (B) ratio (W/B) of 2 should have smaller differences in T_o with compact specimens (W/B=2) than 3-point bend specimens with W/B=1, like PCVN.

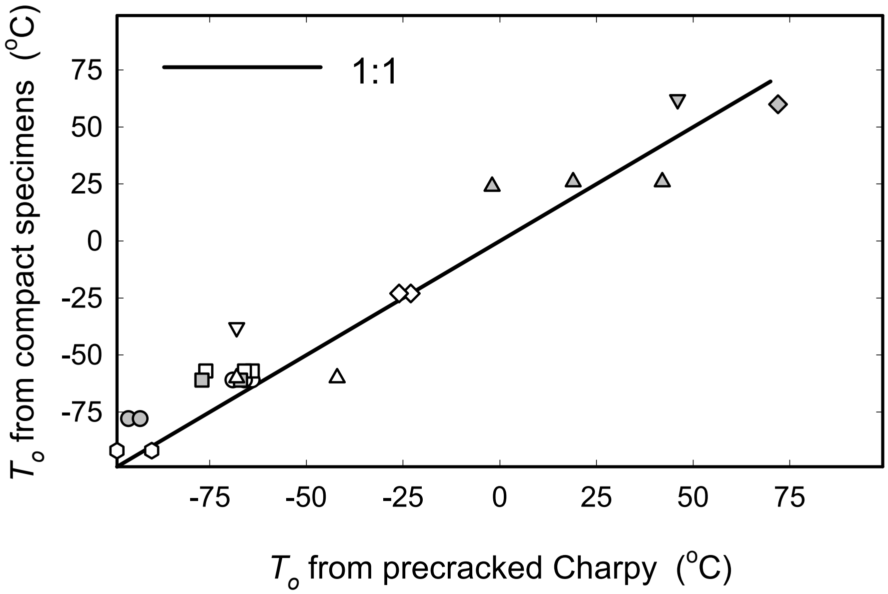

Figure 1. Comparison of T_o values generated from PCVN and C(T) specimens from Ref. [6].

The present results provide additional experimental data on this topic. In the case of HSST Plate 02 and JRQ Plate, there were 3-point bend specimens of both W/B=2 and W/B=1 configurations. Results from these plates are illustrated on Figures 2 and 3, respectively.

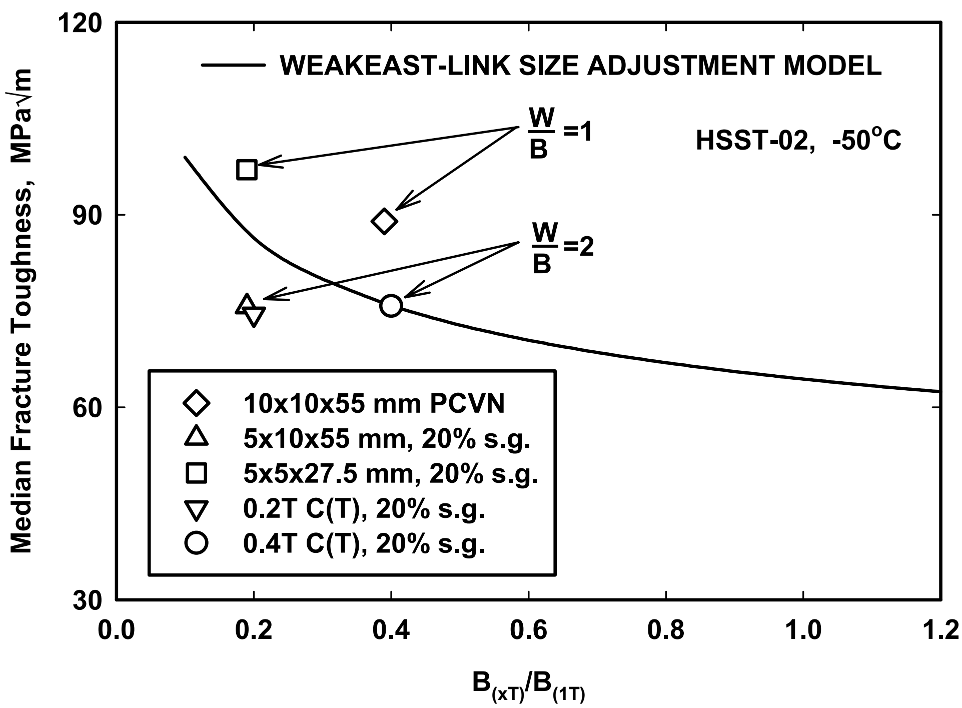

Figure 2. Median fracture toughness values of HSST Plate 02 specimens with different width (W) to thickness (B) ratios.

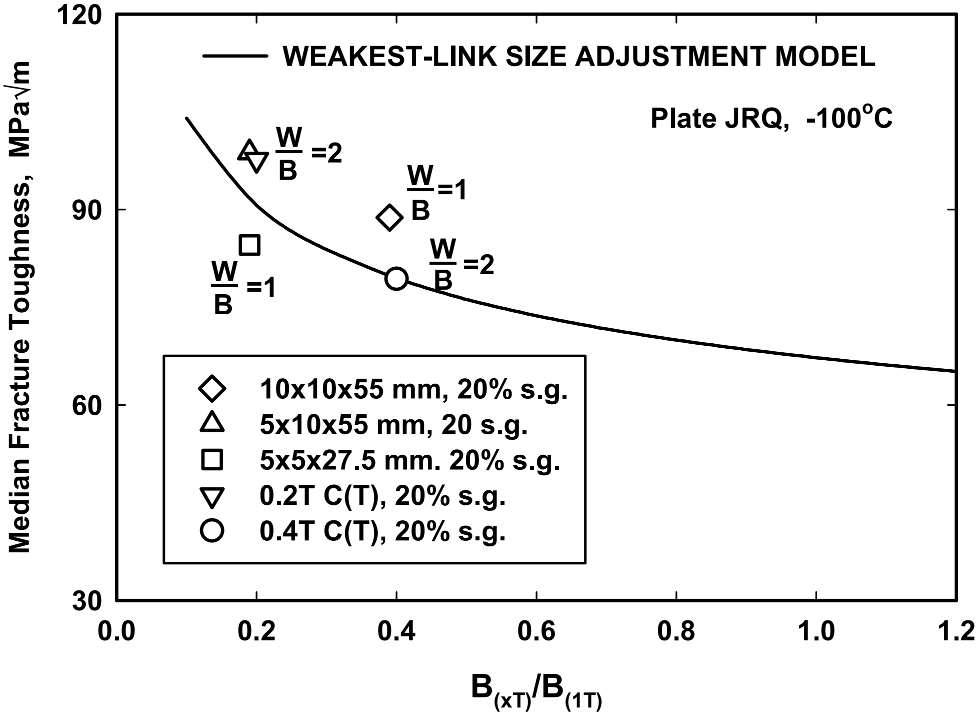

Figure 3. Median fracture toughness values of JRQ Plate specimens with different width (W) to thickness (B) ratios.

On these figures, median fracture toughness values determined with Eq. (4) are plotted versus thickness relative to thickness of the 1TC(T) specimen. The weakest-link size adjustment model by Eq. (3) is shown as a solid line through the 0.4TC(T) median fracture toughness value. Data are compared at the same test temperature; -50°C for Plate 02 and -100°C for Plate JRQ. In the present study, only PCVN specimens of HSST Plate 02 were not side-grooved. All other specimens were 20% side-grooved.

These results consistently indicate that the median fracture toughness values from PCVN specimens are higher than the median fracture toughness of 0.4T C(T) specimens. It is important to note that these specimens are of the same thickness, thus, there is no size adjustment involved in these comparisons. At the same time, 0.2T C(T) and 5x10x55mm 3-point bend specimens exhibited very similar median fracture toughness values in both cases. These specimens have similar thicknesses and the same W/B ratio of 2. Results from 5x5x27.5 mm specimens are rather inconsistent. On the other hand, those specimens have the most invalid data points.

The present results on JRQ Plate are in good agreement with available data on this material from several coordinated programs performed by IAEA with broad international participation [12]. It is well known now that this material has a substantial through thickness properties distribution. However, the general trend is for T_o values from PCVN specimens to be much lower, on order of 20°C, than for C(T) specimens, with results from a large number of laboratories.

In Figure 4, the median fracture toughness value from PCVN specimens of HSST Plate 13 is compared with median fracture toughness values produced from testing of a relatively large number of different size compact specimens in Ref. [3]. The solid line on this figure represents the weakest-link size adjustment by Eq. (3) based on $K_{Jc\,(med)}(1T)$ = 111.33 MPa / m and T_o = -83°C derived from analysis of all compact specimens tested -75°C in Ref. [3]. First of all, it is pointed out how remarkably well those individual median fracture toughness values from different compact specimens follow the Eq. (3) model. In contrast, the median fracture toughness for the PCVN specimens is significantly higher than the trend from the compact specimens which agrees well with available observations. Note however, that out of 6 PCVN specimens tested only one exhibited valid $K_{Jc\ (med)}$.

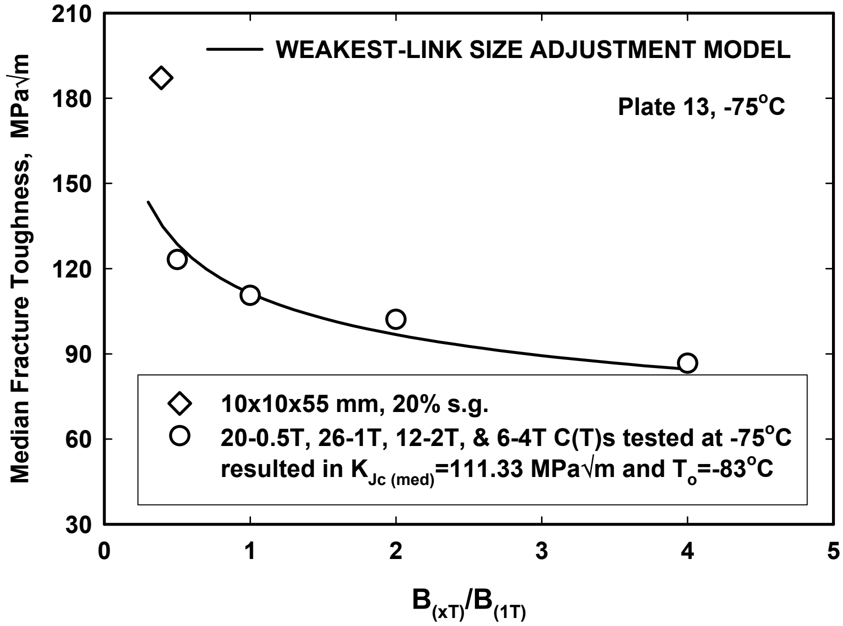

Figure 4. Median fracture toughness values of HSST Plate 13

Results from Modified A302B Plates Z2 and Z7 are illustrated in Figure 6. As in the previous cases, the median fracture toughness derived from PCVN specimens tend to be higher than one would expect from 1T C(T) data using weakest-link size adjustment model by Eq. (3). The results from these plates show that variability exists in the differences that likely results from statistical factors.

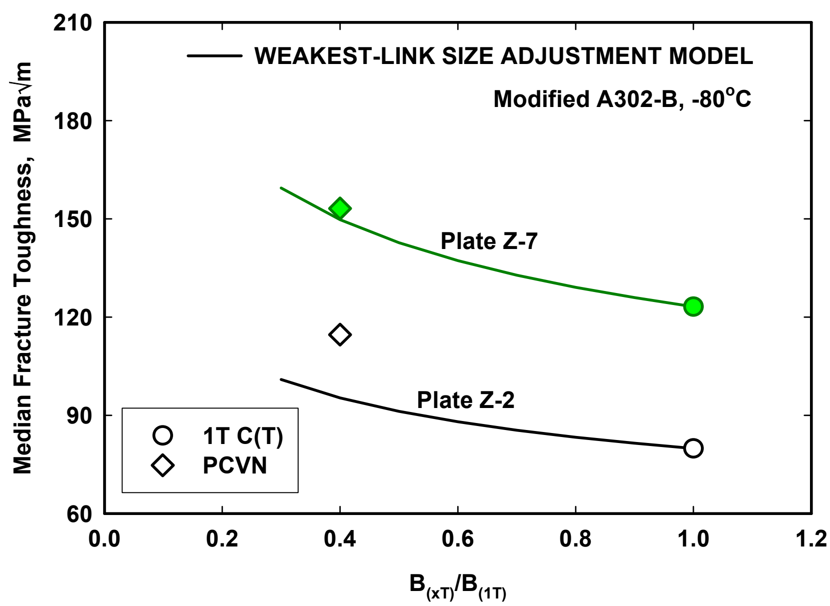

Figure 5. Median fracture toughness values of Modified A302B Plates Z2 and Z7 from 1T C(T) and PCVN specimens.

Additionally, the HSSI Program has recently been involved in the Materials Properties Council cooperative testing program with PCVN specimens of two RPV steels, one of which was HSSI Weld 72W [13]. The results showed T_o values from PCVN specimens of the "second batch" being lower (in other words, $K_{Jc\ (med)}$ being higher) than T_o values from the large number of compact specimens from the "first batch" of HSSI Weld 72W. To verify similarity of the two batches, 1T compact specimens from the second batch were machined and tested, to provide a T_o value comparable to that for the first batch. The results showed that the T_o from PCVN specimens was 22°C lower than from the 1TC(T) specimens [14]. The results provide another strong indication that this difference was due to a bias in T_o values between PCVN and compact specimens rather than a difference in material properties.

Overall, the present results indicate that there is a consistent difference in K_{Jc} values derived from compact and 3-point bend specimens, especially from 3-point bend specimens with W/B=1.

SUMMARY

The applicability of small specimens to characterize the transition fracture toughness of pressure vessel steels has been examined by the testing of precracked Charpy and other types of subsize specimens from five different plates. The main focus of this study was to examine the ability of PCVN and smaller size specimens to exhibit the same reference transition fracture toughness temperature, T_o, as larger specimens.

The main results are summarized as follows:

1. The current results showed that T_o determined from PCVN specimens with W/B=1, on average, is lower than T_o determined from compact specimens with W/B=2. This observation agrees with recently published results from different laboratories.
2. At the same time, 5x10x55 mm three-point bend specimens with W/B=2 exhibited T_o values that were very similar to T_o values derived from compact specimens. Additional experimental data with larger thicknesses (10 mm and 25.4 mm for example) are needed to confirm this observation.
3. The present results indicate that there is a need for further experimental and analytical work to resolve the issue of the observed differences between compact and PCVN specimens from both constraint and J-integral formulas points of view.

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