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Influence of Loading Rate on the Fracture Toughness of High Strength Structural Steel

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Abstract

It is known that rates of loading influence the fracture behaviour of most ferritic steels. High loading rates could change a stable ductile tearing behaviour to an unstable brittle fracture by altering the ductile-to-brittle transition curve. This is predicted to be material dependent, with lower strength structural steels showing a larger tensile property loading rate sensitivity compared to high strength structural steels. A programme of mechanical testing was carried out on S690QL and S960QL to determine the influence of loading rate on the fracture behaviour of high strength structural steels with yield strength > 690 MPa and yield-to-tensile ratio above 0.90. The loading rates considered are those anticipated in offshore in-service conditions, with K-rates up to the order of magnitude of 10^6 MPa√m/s. Results from tensile tests show that the strengths of these grade of steels are relatively unaffected by the effect of loading rate. However, brittle fracture, which is controlled by material strengthening as a result of principal stress in front of the crack, is both loading rate and temperature dependent. Results from tests at quasi-static and elevated loading rates show changes in the fracture behaviour in terms of transition temperature. A shift to a higher ductile-to-brittle transition temperature was observed as the loading rate increases. This was associated with a reduction in the fracture toughness value on the lower transition region. The reference temperature, T_0, at a K-rate of 1 MPa √m/s using Master Curve concepts is estimated to be around -116 °C and -108 °C for Charpy-sized pre-cracked and standard (25x25 mm) SENB specimens respectively, under quasi-static conditions for S690QL. The dynamic $T_{0,d}$ is -70.4 °C in the same steel for Charpy-sized pre-cracked specimens at K-rates up to 10^6 MPa √m/s.

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1. Introduction

Often, an understanding of fracture behaviour of steel during experimental testing at different loading regimes helps to prevent some of the potential catastrophic accidents during in-service conditions. It is assumed that a single fracture toughness value (critical value) controls the fracture behaviour of a material [*Wallin (2011)*]. This value describes the crack initiation and subsequent propagation behaviour of the material (the driving force and the material resistance). The driving force is the combination of material flaw size and loading conditions, while the material resistance is the ability of the material to resist propagation of these flaws or cracks [*Wallin (2011)*]. The strain-hardening exponent (n) influences fracture behaviour [*Bannister and Trail (1996)*]. It has been demonstrated that crack opening is enhanced by a high yield-to-tensile (Y/T) strength ratio and, hence low strain-hardening capacity [*Bannister (1999)*].

The effect of loading rates on the difference in the dynamic and quasi-static fracture toughness values for a steel material relies mainly on the material's deformation properties, with the brittle cleavage fracture process remaining the same, but the difference in fracture toughness predicted to be material dependent [*Wallin (2011)*]. In some cases, ductile fracture is considered to have a positive rate dependence with an enhancement of dynamic ductile fracture toughness, however this factor is considered negligible when performing structural analysis [*Walters and Przydatek (2014)*]. Brittle fracture toughness of ferritic steels generally reduces in value with increasing loading rate (a negative rate dependence) [*Wiesner and MacGillivray (1999), Wallin (2011)*]. The mechanism of brittle fracture is mainly controlled by the stress state in front of the crack, and less affected by adiabatic heating because its initiation is in the region of high stresses where the plastic strains are relatively small, further away from the crack tip [*Wallin (2011)*]. This implies that the yield strength and strain-hardening properties of a steel material have an effect on the brittle fracture toughness resistance.

A significant impact may be experienced on the ductile-to-brittle-transition curve where a brittle fracture toughness may drop up to 80% from the measured toughness at quasi-static conditions [*Wallin (2011)*]. Thus, the effect of loading rate must be accounted for in the estimation of brittle fracture toughness resistance of high strength structural steel (HSSS) with high Y/T ratio above 0.90. In this paper, a short survey and outlook of the effect of loading rate on fracture toughness of ferritic steel is presented alongside the structural implication of high Y/T ratio in ferritic steel. Finally, test data at quasi-static and elevated loading rates show how fracture toughness behaviour in terms of the transition temperature of S690QL and S960QL with Y/T ratio above 0.90 changes due to elevated loading rate.

Nomenclature

a_0	initial crack length (mm)
n	Strain-hardening exponent
σ_y	Yield strength (MPa or N/mm^2)
B	specimen thickness (mm)
Y/T	ratio of yield to tensile strength
HAZ	Heat affected zone
1T	specimen size at 1 in thickness, i.e. B = 25.4 mm
E	Modulus of elasticity (GPa)
K	Stress intensity factor (MPa√m)
$\dot{K}$	Stress intensity factor loading rate (MPa√m/s)
K_{JC}	elastic-plastic equivalent stress intensity factor derived from J-integral at onset of cleavage fracture
$\dot{\varepsilon}$	Strain rate (s^{-1})
a_0/W	ratio of the initial crack growth to the width
SENB	single edge notched bend
W	specimen width, measured in the direction of the notch (mm)
ΔT	Temperature shift (°C)
T_0	quasi-static reference transition temperature (°C)
$\sigma_y^{T_0}$	Yield strength estimated at T_0 (MPa)

$T_{0,d}$	dynamic master curve reference temperature (°C)

2. Outlook of high strength structural steel and loading rate effect on fracture toughness of ferritic steel

2.1. Application and structural implication of high Y/T ratio in high strength structural steel

High strength structural steels (HSSS) are often preferred to conventional lower strength structural steels (LSSS) for special structural element designs when sectional weight reduction of heavy steel structures, as used in offshore industry (lifting appliances, topsides), construction industry (bridges and buildings) and off-highway equipment (fixed and mobile cranes, excavators, earthmoving), is important, *Commissions of the European Communities (1988), Willms (2009)*. The fracture behaviour and performance of LSSS is well known and established in the standards. In fact, most of the design codes relate the design formulae to LSSS with Y/T ratio below 0.85 and yield strength up to 500 MPa for offshore design requirements, *Billingham et al. (1997) and Billingham et al. (2003)*. The same level of confidence is yet to be achieved for HSSS and, the high Y/T ratio that comes with it. The concern is that these HSSS grades obtained their strength at the expense of ductility and strain-hardening capacity; properties which provide a sense of extra safety in avoidance of failure should service loads exceed yield. So design codes that utilise these properties to deliver safety when using low strength structural steel grades, with a Y/T ratio below 0.85, may not currently be applicable for modern high strength steels. An example of the approach to HSSS is the American Petroleum Institute (API) practice which recommends a value for certain tubular joints yield level of 66% (two-thirds) tensile strength with yield strength property up to 500 MPa [*API 2A-WSD (2014)*]. However, a re-evaluation conducted and incorporated into the newest edition of the standard suggested that a Y/T ratio of 0.80 for joints could be used provided that an adequate ductility is demonstrated in both HAZ and parent metal with 500 MPa $< \sigma_y \leq$ 800 MPa [*API 2A-WSD (2014)*]. Also, Eurocode 3 (Design of steel structures), allows a Y/T value up to 0.95, whereas the UK Annex of the same standard recommends 0.91 as a maximum [*Eurocode 3: Part 1-12 (2007)*, *UK National Annex to Eurocode 3: Part 1-12 (2007)*]. As confidence in the structural performance of these grades is established they become more accepted into the standards. Ttypical stress-strain curves for modern high strength steel and conventional low strength steel are given in Fig. 1.

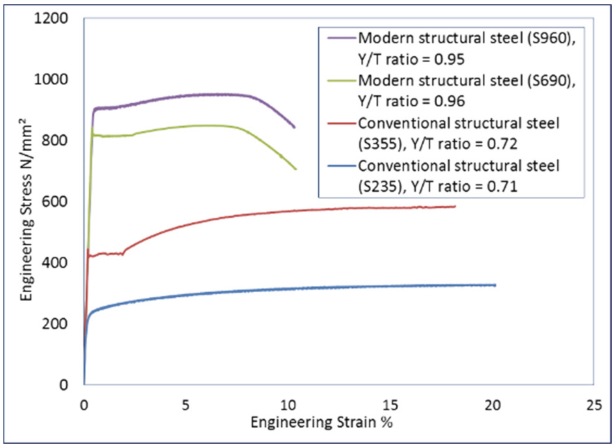

Fig. 1. Stress-strain characteristics of modern QT high strength structural steel and conventional low strength structural steel. Courtesy of TWI Ltd)

In an elastic design approach, the working stress is usually taken as a proportion of the yield stress, with typical values around 60% of yield strength in normal loading and up to 80% in severe loading, ensuring that load resistance falls within the linear region of the stress-strain curve of the component, making the Y/T ratio irrelevant in such elastic cases [*Healy et al. (1995)*]. However, in the case of plastic design (design concept in which the structure is able to locally yield and redistribute load without major failure or total collapse), the Y/T ratio becomes relevant in the post-yield behaviour of steel [*Healy et al. (1995)*]. Therefore, in engineering terms, the Y/T ratio can be said to be the parameter which represents the ability to withstand plastic loading and the basic measure of deformation capacity of a material [*Bannister and Trail (1996)*]. The increase in nominal yield strength affects the extent of plastic stability in the form of reserve strength induced by strain-hardening indicated by an increased Y/T ratio [*Healy et al. (1995)*, *Bannister and Trail (1996)*]. To this end, a maximum Y/T ratio is imposed in design codes to ensure steel structures have adequate room to redistribute load before major failure [*Bannister and Trail (1996)*].

However, integrity performance of HSSS with Y/T ratios between 0.8 and 0.95 in structural designs such as pipelines, pressure vessels, building constructions, shows that high Y/T ratio does not necessarily signify poor fracture performance, which depends on a number of other factors [*Brockenbrough, R. L. and Associates Inc., (1995), Bannister and Trail (1996), Willms (2009)*]. The Y/T ratio per se is not the only governing parameter that influences the plastic response of a material, other related characteristics such as strain-hardening exponent, ductile tearing resistance, and overall global deformation are important factors to take into account when considering the practicality of using high Y/T ratio as a measure of plastic strain capacity of a cracked component [*Bannister (1999)*].

2.2. Reference survey on the effect of loading rate on the fracture toughness of ferritic steel

The one common effect of loading rate on the fracture toughness of most ferritic steels is the increase in the transition temperature [*Francis et al. (1978), Wiesner and MacGillivray (1999), HSE report, OTO (1999), Burdekin et al. (2004), Wallin (2011), Walters and Przydatek (2014), Gotoh (2015)*]. The extent of the shift is highly dependent on the nominal yield strength [*Wiesner and MacGillivray (1999), HSE report, OTO (1999)*]. Perhaps one of the reasons why toughness requirements must be adjusted according to the yield strength of the steel for normal or extreme loading conditions [*Shoemaker (1981)*]. The effect of increasing loading rate is more pronounced on the lower strength steel grades, whereas, high strength steel exhibits less loading rate sensitivity depicted by the shift in transition temperature [*Wiesner and MacGillivray (1999)*]. The increasing loading rate does not necessarily mean an increase in ductile toughness on the upper shelf [*Wiesner and MacGillivray (1999)*].

The effect of loading rate on the fracture toughness is more sensitive to temperature and the rate of change of the crack tip stress intensity factor loading rate ($\dot{K}$) rather than the overall strain rate ($\dot{\varepsilon}$) of the material in a cracked component [*Francis et al. (1978)*]. It is important to note that whilst the fracture mechanical loading rate is mostly approximated and expressed in terms of stress intensity factor loading rate for linear elastic conditions, the loading rates in structural engineering are usually considered in terms of strain rates [*Wallin (2011)*]. The use of the strain rate to determine a single effective loading rate value in a cracked specimen could lead to a crude estimation in a real scenario [*Wallin (2011)*]. Hence, the use of stress intensity factor loading rate as a mean of expressing fracture mechanical loading rate. However, a relationship exist between $\dot{K}\ and\ \dot{\varepsilon}$, Eq 1, for a cracked component within the elastic region just outside of the crack tip plastic zone [*Burdekin et al. (2004)*].

$$\dot{\varepsilon} = \frac{2\sigma_y \dot{K}}{E\,K} \tag{1}$$

In summary, the general trend shows that the effect of loading rate on the fracture toughness of ferritic steels was mainly concerned with defining the fracture transition temperature shift (ΔT_0) to a higher temperature value using an empirical approach [*Burdekin et al. (2004)*]. The Master Curve is a statistical method describing the fracture characteristics in the transition region based on the reference transition temperature T_0, and this forms the basis of ASTM 1921 testing standard [*ASTM 1921-15a*$^{\varepsilon 1}$]. The concept has been applied to a wide range of yield strengths from 200 to 1000 MPa to predict ΔT_0, Eq 2, as a result of loading rate induced temperature shift [*Wallin and Mahidhara (1997)*].

$$\Delta T_0 = \frac{T_0 \cdot \ln(\dot{K}_I)}{\Gamma - \ln(\dot{K}_I)} \tag{2}$$

The function Γ is the loading rate effect fitting parameter given in Eq 3, and $\dot{K}_I$ is the average loading rate of the elevated rate tests.

$$\Gamma = 9.9 \cdot exp\left[\left(\frac{T_0 + 273.15}{190}\right)^{1.66} + \left(\frac{\sigma_y^{T_0}}{722}\right)^{1.09}\right] \tag{3}$$

3. Materials and experimental methods

3.1. Materials

The materials studied are S690QL (WELDOX 700 EZ) and S960QL (WELDOX 960 HZ) with Y/T ratio in the region of 0.96 and 0.95 respectively, which are typical high strength structural steel grades used in offshore applications. These two materials were delivered in quenched and tempered conditions, and satisfy the -40 °C minimum impact energy requirement in the transverse direction. The delivery condition was in accordance with BS EN 10025:6: +A1 (2009). The grade designation stands for the following: S – Structural Steel, 690/960 – Minimum Yield Strength (MPa), Q – Quenched and Tempered production process, L – Low Notch Toughness Testing Temperature at -40 °C.

3.2. Experimental methods

Single edge notched bend (SENB) specimens were prepared and tested to BS EN 7448 part 1 in the case of quasi-static condition and BS EN 7448 part 3 and BS ISO 26843:2015 in the case of elevated loading rate. Specimens were taken at ¼ depth of full thickness and notched through thickness in the Y-X orientation. The specimens were fatigue pre-cracked with the nominal a_0/W of 0.5. Two datasets were generated for S690QL tests, a standard specimen configuration (WxB=25x25 mm) and a Charpy-sized pre-cracked specimen (WxB=10x10 mm). For S960QL, only Charpy-sized pre-cracked specimens (WxB=10x10 mm) were tested. In this paper, tests done at 0.005 mm/s refer to quasi-static (QS) loading rates, and 5400 mm/s describes tests carried out at elevated loading rates (dynamic). In terms of fracture mechanical loading rate expressed as K-rate, the QS K-rate is within the range 0.5 to 3 MPa√m/s specified by BS EN 7448 part 1. In order to simulate the possible loading rates that offshore and marine structures could be subjected to in-service, Table 1, the average elastic stress intensity factor loading rate (K-rate) was calculated by fitting the linear part of the data describing the stress intensity factor-time trace. An order of magnitude of 10^6 MPa√m/s was achieved for the 5400 mm/s test speed.

Table 1. Typical loading rates in some engineering components. Data taken from *Wiesner and MacGillivray (1999, Burdekin et al. (2004), Walters and Przydatek (2014)*

Applications	Strain Rate $\dot{\varepsilon}$ (s^{-1})	Stress Intensity Factor Loading Rate $\dot{K}$ (MPa√m/s)
Storage tanks, buried pipelines, pressure vessels	10^{-6} to 10^{-4}	10^{-2} to 1
Self-weight, wind and wave loading	10^{-4} to 10^{-2}	1 to 10
Bridges, cranes and earthmoving	10^{-2} to 0.1	10 to 10^3
Earthquake loading and marine collision	0.1 to 10	100 to 10^4
Land transport and aircraft undercarriage	10 to 1000	10^3 to 10^6
Explosion and ballistics	10^4 to 10^{6+}	10^7 to 10^{10+}

4. Results and Discussion

4.1. Tensile properties

Initial stress-strain curves generated from the tension tests, Figs. 2a and 2b, shows that the tensile properties of high strength steels are relatively unaffected by the effect of strain rate. This is discussed in detail by *Alabi et al. (Journal paper under review)*. Yield strength amplification of only about 6% and 3% were recorded for S690QL and S960QL at 4 s^{-1} strain rate respectively when compared to quasi-static (0.0002 s^{-1}) strain rate tests [*Alabi et al. (Journal paper under review)*]. Therefore, it could be said that strain rate sensitivity of ferritic steels decreases as the nominal yield strength increases.

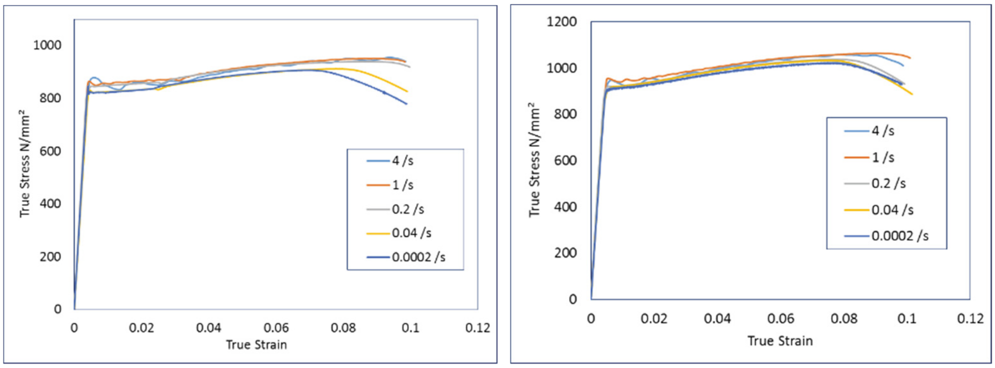

Fig. 2. (a) Effect of strain rate on the stress-strain characteristics of S690QL; (b) S960QL between 0.0002 s^{-1} and 4 s^{-1} strain rates. (Courtesy of TWI Ltd)

4.2. Fracture toughness results

Fracture toughness results at quasi-static loading conditions (QS) for 10x10 mm and 25x25 mm SENB tests are summarised in Tables 2a and 2b respectively.

Table 2a. Fracture toughness data for S690QL at QS using Charpy-sized pre-cracked (10x10 mm) SENB

S690QL	Test temperature (°C)	J (N/mm)	K_{JC} 1T (MPa √m/s)	Test speed (mm/s)
M01-87	-100	48.82	88.89	0.005
M01-94	-100	131.18	143.09	0.005
M01-98	-100	206.49	178.48	0.005
M01-99	-100	174.72	164.51	0.005
M01-100	-100	79.14	112.06	0.005
M01-106	-120	15.17	51.51	0.005
M01-112	-120	43.44	84.33	0.005
M01-113	-120	41.09	82.13	0.005
M01-114	-120	39.34	80.45	0.005

Table 2b. Fracture toughness data for S690QL at QS using standard (25x25 mm) SENB

S690QL	Test temperature (°C)	J (N/mm)	K_{JC} (MPa √m/s)	Test speed (mm/s)
M01-115	-100	68.78	126.55	0.005
M01-116	-100	57.72	115.94	0.005
M01-117	-100	111.08	160.83	0.005
M01-118	-100	20.78	69.56	0.005
M01-119	-100	38.97	95.26	0.005
M01-120	-100	35.45	90.86	0.005
M01-121	-100	51.29	109.29	0.005

4.3. Master Curve predictions

The Master Curve concept is only intended for describing materials fracture toughness in the transition region of the ductile-to-brittle transition curve (DBTC). Therefore, data from tests at -100 °C and -120 °C have been considered for the calculation. The estimated T_0 determined from both Charpy-sized pre-cracked and 25 mm thick specimens are -116 °C and -108 °C respectively, Figs. 3a and 3b under QS conditions. The master curve theory should mean both datasets predict the same T_0, but it is important to mention that a difference of about 8 °C is observed due to the partial loss of crack-tip constraint. This effect is described by *Joyce and Tregoning (2005)*.

For this work, a comparison between QS and dynamic results is being sought, so the same Charpy-sized pre-cracked specimens were used throughout to avoid the influence on the shift in transition temperature. The dynamic master curve reference temperature $T_{0,d}$ calculated is -70.4 °C, Fig. 4. A shift of about 45.6 °C is therefore observed for S690QL.

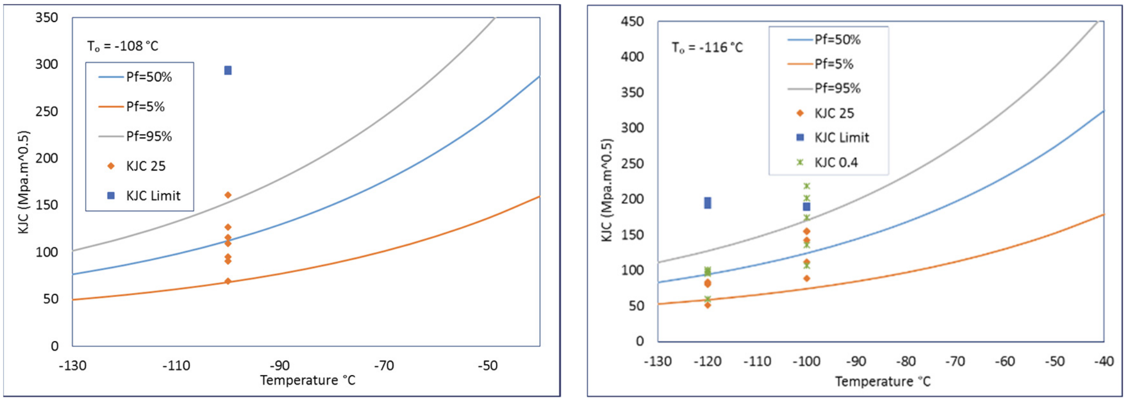

Fig. 3. (a) QS Master Curve for 1T specimens for S690QL; (b) QS Master Curve for 1T specimens based on 0.4T (10 mm) data for S690QL. (Courtesy of TWI Ltd)

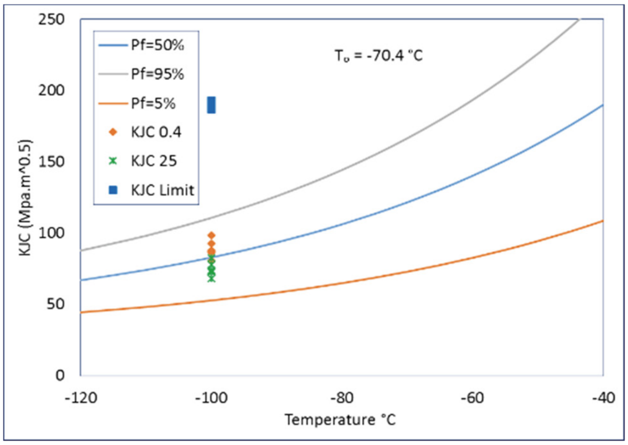

Fig. 4. Dynamic Master Curve for 1T specimens based on 0.4T data for S690Q. (Courtesy of TWI Ltd)

Given that the results of the S690QL tests shows that the ASTM 1920-15a T_0 shift prediction with dynamic loading compares well the experimental estimation, the ΔT_0 prediction for S960QL (which was not fracture toughness tested at elevated loading rate) is 29 °C. Therefore, as observed with the tensile test results, high strength steel is less affected by the effect of increased loading rates up to those studied (typical offshore in-service loading rate). S960QL shows less sensitivity to the effect of loading rate because of its higher strength when compared to S690QL. However, the cleavage fracture toughness still reduces for both steels when loading rate is increased. The Master Curve dynamic predictions have been shown to reasonably predict the transition fracture behaviour of S690QL at K-rates up to 10^6 MPa √m/s.

5. Conclusions

The effect of loading rate on the fracture toughness of S690QL and S960QL has been studied. Based on the investigation, it can concluded that:

- The T_0 estimated for S690QL at QS and dynamic conditions based on the Master Curve, with tests performed at -100 °C using Charpy-sized pre-cracked SENB specimens, is -116 °C and -70.4 °C respectively. Here the ΔT_0 from QS conditions to 10^6 MPa√m/s is 45.6 °C
- The influence of loading rate on fracture toughness can be determined using Charpy-sized pre-cracked SENB specimens.

- A temperature shift of about 40 °C and 29 °C for S690QL and S960QL respectively is predicted for QS conditions up to a K-rate with an order of magnitude of 10^6 MPa√m/s, based on ASTM E1921-15a with prior knowledge of T_0 under QS conditions.
- Although, the tensile properties of very high HSSS is fairly insensitive to strain rates up to 4 s^{-1}, the fracture toughness behaviour is affected by dynamic loading.

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