A State-of-the-Art Review of High Performance Steel for Bridge Design

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Résumé

Une nouvelle nuance d'aciers à haute résistance fait son apparition à travers le monde. Ces aciers, dits "haute performance" (HPS), offrent d'excellentes propriétés en termes de résilience, de ductilité et de soudabilité. Ils permettent des ponts novateurs, plus légers et économiquement intéressants. L'objectif de cet article est de clarifier ce que l'on entend par "haute performance" et de décrire quelques propriétés qui distinguent ces aciers des aciers conventionnels. Cet article abordera également les besoins en connaissances sur le comportement des HPS à l'état limite de fatigue, et l'état actuel de la recherche menée au Canada pour évaluer le résistance à la fatigue des HPS soudés.

Abstract

A new class of high strength steels with excellent toughness, ductility, and good weldability is emerging world-wide. High performance steel (HPS) is resulting in innovative bridge designs with reduced weight and cost savings. The purpose of this paper is to define what is meant by the term "high performance" and to describe some of the properties that distinguish HPS from conventional grades. The paper also identifies gaps in the knowledge of HPS at the fatigue limit state. Finally, an overview of research on HPS currently underway in Canada that will assess the fatigue performance of welded HPS is described.

1.0 Introduction

It is often assumed that there is a trade-off between increased strength and reduced ductility and toughness for structural steels. However, the need for innovative designs has resulted in new grades of steel being developed in the United States, Europe, and Japan that do not follow this assumption. These steels, which are called High Performance Steels (HPS), have nominal yield strengths that range from 485 MPa to 900 MPa, yet exhibit excellent ductility, toughness, and corrosion resistance. HPS can be welded with greater ease than many steels developed in the past. Therefore, HPS is an excellent candidate for bridge construction, and in fact is being used to develop many innovative bridge designs (Sause *et al.* 2001, 2002; Azizinamini *et al*. 2004). HPS can produce cost savings in bridge construction because the number and size of girders can be reduced due to the increased strength. The toughness and corrosion resistance of HPS makes it particularly attractive for bridges constructed in Canada's harsh climates. The Ministry of Transport of Québec is the first transportation ministry in Canada to propose using HPS for a bridge project.

This paper first provides a brief review of the development of high-strength steels around the world and then focuses on a grade of HPS developed in the United States, ASTM A709 – HPS 485W, which is rapidly being adopted by bridge designers there. The current state of use, design implications, and research on HPS are outlined. In particular, research programs underway at the University of Alberta and Queen's University on the fatigue performance of HPS are described.

2.0 Development and Properties of High Performance Steels

Use of high-strength steels for bridge construction in Japan dates back to the 1960s (Miki *et al.* 2002). Several hundred bridges have been constructed using 500 MPa and 600 MPa yield strength steel, and steel with a nominal yield strength of 800 MPa has also been used on several projects. These steels typically require pre-heating between 100ºC and 120ºC before welding and sometimes post-weld heat treatment in order to prevent hydrogen assisted cracking of the weld. However, in 1992 a new 800 MPa grade of steel was developed that requires pre-heats of only 50ºC (Miki *et al*. 2002).

In Europe, a variety of high-strength steels with yield strengths from 460 MPa to 690 MPa are available for bridge applications. European structural steel standard EN 10025: 2004 grade S460ML, which has a nominal yield strength of 460 MPa, can be welded at room temperature for plate thicknesses up to 90 mm and has a specified minimum Charpy V-notch (CVN) energy of 27 J at -50ºC.

The development of high performance steel grades in the United States began in 1992 as a co-operative effort among the Federal Highway Administration (FHWA), the U.S. Navy, and the American Iron and Steel Institute (AASHTO 2003). The intention was to develop grades of steel that were stronger than the common 350 MPa yield strength steel typically used for bridge construction, but with high toughness and improved weldability. A 485 MPa grade of HPS was the first developed, and is specified in ASTM A709 as grade HPS 485W (the designation "W" stands for "weathering").

High performance steel HPS 485W was developed to replace the conventional 485W steel, which has been available for bridge construction for years. Its use, however, was limited because it requires more precise control of welding and fabrication practices than lower strength steels, which resulted in only a few bridges being built with steel of this grade. The new HPS 485W grade promises to overcome these drawbacks and allows the full potential of this strength grade to be realized.

Tests by Chen *et al.* (2003) showed that HPS 485W has excellent ductility, with 23% elongation over a 50 mm gauge length at rupture and 44% reduction of area. HPS 485W has a specified minimum CVN value of 48 J at -23ºC for fracture critical members, and requires pre-heating to only 20ºC for plates up to 64 mm thick (AASHTO 2003). Figure 1 shows a comparison of CVN results for three heats of HPS 485W, obtained from plates of three different thickness, and ASTM grade A7 structural steel, which has a nominal yield strength of approximately 230 MPa. The toughness of different HPS heats was found to vary considerably and the results presented in Figure 1 show two heats of steel, designated HPS (HT), with considerably higher energy levels than the third heat, designated HPS (LT) (Chen *et al.* 2003). The high toughness of HPS 485W at low temperatures is an important consideration for bridges in the Canadian climate.

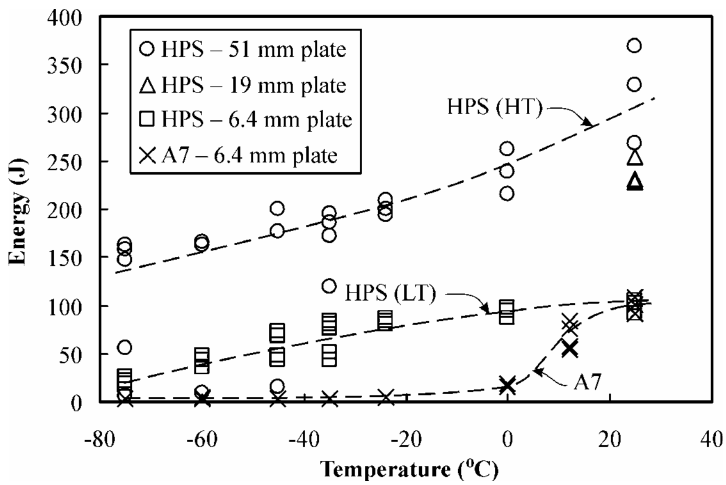


Figure 1 – Charpy V-notch energy vs. temperature (Chen *et al.* 2003).

Table 1 compares the chemical compositions of ASTM A709 grades 485W and HPS 485W steel. Also shown is the composition of EN 10025: 2004 grade S460ML and CSA G40.21 350WT steel, used as a basis of comparison with commonly used highway bridge steel. Both high performance steel grades have significantly reduced carbon, phosphorus, and sulfur contents compared to the conventional grades 485W and 350WT. Both the carbon content itself and the carbon equivalent represent measures of weldability, i.e., the ease with which the steel can be welded without exhibiting susceptibility to hydrogen induced cracking. If the carbon content is less than 0.11 %, the hardness is relatively low even when alloy levels are very high (Patchett *et al.* 2001). These steels are, therefore, not susceptible to hydrogen induced cracking and only minimal precautions are necessary during welding. For steels with carbon contents higher than 0.11%, the carbon equivalent, which also accounts for the effect of alloying elements such as Mn, Si, Cr, Mo, V, Cu, and Ni on hardenability of steel, is a measure of the sensitivity of the welded steel to cracking. Because of their low carbon content, the high performance steels have good weldability even if their carbon equivalent is elevated. On the other hand, grades 485W and 350WT steels listed in Table 1 have a sufficiently high carbon content and carbon equivalent to require some control in the weld procedure (Patchett *et al.* 2001). This control usually consists of preheat, controlling the interpass temperature and the quality and handling of the welding electrodes to minimize hydrogen intake, and post-weld heat treatment.

Although the chemical composition of HPS is the main factor in their improved weldability, a reduction of carbon content results in a decrease in strength. In order to achieve the high strength that is characteristic of HPS, the combination of alloying elements and production by quenching and tempering or thermo-mechanical controlled processing (TMCP) results in a fine grain microstructure that possesses both high strength and toughness. Because the quenching and tempering process generally limits plate lengths to approximately 15.2 m, TMCP practices have been developed to produce HPS 485W up to 50 mm thick and to 38 m long (Lwin 2002).

Table 1: Chemical compositions of conventional and high performance steels.

Element	**Chemical composition, %**			
	ASTM A709 Grade 485W	**ASTM A709 Grade HPS485W**	**EN 10025 Grade S460ML**	**CSA G40.21 Grade 350WT**
Carbon (C)	0.19 max	0.11	0.08	0.22
Manganese (Mn)	0.80 – 1.35	1.10 – 1.35	1.65	0.80 – 1.50
Phosphorus (P)	0.035 max	0.02 max	0.011	0.03 max
Sulfur (S)	0.04 max	0.006 max	0.002	0.04 max
Silicon (Si)	0.20 – 0.65	0.30 – 0.50	0.45	0.15 – 0.40
Copper (Cu)	0.20 – 0.40	0.25 – 0.40	0.17	—
Nickel (Ni)	0.50 max	0.25 – 0.40	0.19	—
Chromium (Cr)	0.40 – 0.70	0.45 – 0.70	—	—
Vanadium (V)	0.02 – 0.10	0.04 – 0.08	—	—
Molybdenum (Mo)	—	0.02 – 0.08	—	—
Aluminum (Al)	—	0.010 – 0.040	—	—
Nitrogen (N)	—	0.015 max	—	—
Carbon Equivalent*	0.45 – 0.64	0.43 – 0.56	0.38	0.35 – 0.47

* As defined in ASTM A992 (ASTM 2000)

Another beneficial feature of HPS is high corrosion resistance. The addition of Cu, Cr, and Ni stabilizes the oxide layer forming on the surface when exposed to wet and dry cycles, providing the steel substrate with protection against corrosion. HPS 485W satisfies the composition requirements of ASTM specification G101 (ASTM 1997) for weathering steels suitable for use in the unpainted condition. HPS has slightly better atmospheric corrosion resistance than conventional weathering steels; the atmospheric corrosion resistance index, as measured in accordance with ASTM G101, for conventional weathering grades is 6.0, while the index for HPS 485W is 6.5 (Lwin 2002). This gives designers the option of eliminating painting in many bridge locations and requires only limited painting in others. Because experience has shown that eliminating painting can reduce the life-cycle cost of many steel structures, this property is considered essential to call a steel “high performance.”

Approximately 200 bridges in the United States have been constructed using HPS 485W. Based on this experience, guide specifications for bridge construction using HPS have been published by AASHTO (2003). This experience indicates that the most cost-effective use of HPS is in hybrid girders. A parametric study conducted by FHWA of two-span continuous plate girder bridges with span lengths from 30 m to 75 m indicated that the optimum girders used ASTM A709 grade 345W (nominal yield 345 MPa) steel for all webs and positive moment top flanges, and HPS 485W for the negative moment top flanges and all bottom flanges (AASHTO 2003). Girder designs consisting entirely of HPS 485W steel were 13 to 20% lighter than those fabricated entirely from grade 345W, but were about 3% more expensive due to the higher cost of HPS material. As HPS material becomes more common in the marketplace, its cost is likely to decline.

3.0 Fatigue Research on High Performance Steels in Canada

The fatigue limit state is an important consideration for bridge designers, and is most likely to govern in the vicinity of welded details. Welding creates stress concentrations, flaws, and tensile residual stresses that significantly reduce the fatigue resistance of the welded detail as compared to the base material. Extensive research and testing of typical welded steel details was carried out in the 1960s and 1970s (Fisher and Wright 2000). This work showed that for welded steel details subjected to fatigue, the number of cycles to failure depends only on the detail type and the applied stress range. The current fatigue design curves, such as those given in CSA standard S6 (2000) and AASHTO (1998), are based on these results. Structural details are classified on the basis of the severity of the stress concentration, ranging from Category A (least severe) to Category E1 (most severe). A fundamental assumption of these curves is that the grade of steel does not have an effect on fatigue performance.

There is currently no definitive answer on the benefit of HPS at the fatigue limit state. The AASHTO (2003) guidelines for fabrication with HPS do not specifically mention fatigue. The current practice is to assume that HPS does not have a benefit over conventional steel grades, and apply the common fatigue design curves to HPS. This creates a dilemma for designers using HPS. On the one hand, the improved strength of HPS is beneficial at ultimate limit states, and can lead to more economical designs. However, the current approach to designing for fatigue of HPS does not provide any benefit. It was shown by Sause (1996) that the full benefits of HPS may not be possible because the fatigue limit state is likely to govern in many cases.

There has been little fatigue testing of welded HPS 485W reported in the literature to support the assumption that it has no benefit at the fatigue limit state. Fisher and Wright (2000) and Wright (2003) tested HPS 485W Category B and C details. Approximately five Category B specimens, each subjected to a stress range of 120 MPa, and approximately five Category C specimens subjected to a stress range of 100 MPa were tested. Although the results were found to lie within the scatter of their respective weld detail categories, more tests are required to evaluate fully whether or not HPS provides a benefit for welded details.

It has been known for some time that fatigue resistance in the finite life range is not significantly affected by material strength and toughness. This is clearly illustrated in Figure 2 where the results of fatigue tests on smooth specimens of HPS 485W and A7 steels are presented in the form of strain amplitude (half of the strain range) versus fatigue life curves (Chen *et al.* 2003). The HPS fatigue data presented in Figure 2 were obtained from specimens fabricated along the axis of plate rolling (long.) and transverse to the axis of plate rolling (trans.). (The longitudinal specimens had the fatigue crack propagating in the transverse direction, whereas the transverse specimens had the fatigue crack propagating in the longitudinal (rolling) direction.) All grade A7 specimens were oriented in the transverse direction.

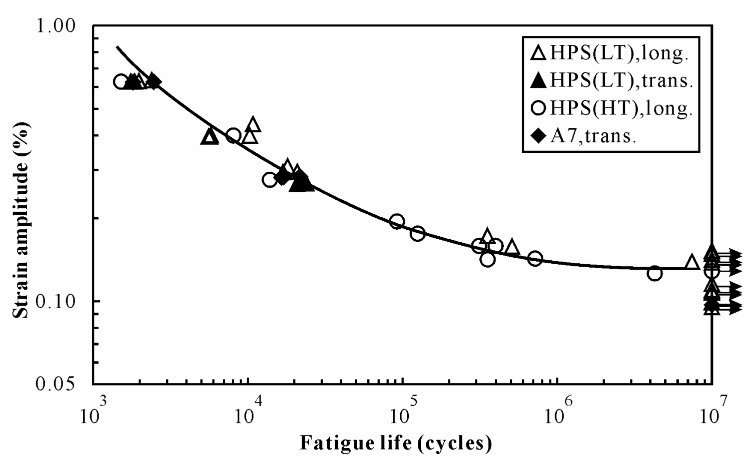


Figure 2 – Fatigue life data (Chen *et al.* 2003).

A potential benefit from the use of HPS is found at the endurance limit, the stress range below which the fatigue life is infinite. The endurance limit is often taken as 35% to 50% of the tensile strength of the steel (Suresh 1998). In the work presented by Chen *et al.* (2003), the endurance limit for HPS was estimated under a fully reversed stress-controlled condition, whereby the stress amplitude was adjusted based on each successive test result in an attempt to converge to the correct value. The test results are presented in Figure 3. The results incorporate stress ratios, $R = \sigma_{min}/\sigma_{max,}$ varying from –0.69 to 0.52 and can be used to estimate the endurance limit. For the HPS(LT) steel, the endurance limit of the smooth specimens is found to lie between 265 MPa (largest stress amplitude with no failures) and 321 MPa (smallest stress amplitude with no run-outs). The estimated endurance limit is thus set at 300 MPa. On the other hand, the endurance limit for the HPS(HT) steel lies below 285 MPa, with two failures at less than 1 million cycles at stress amplitudes of about 285 MPa. The fatigue limit can reasonably be estimated at 270 MPa, with one run-out and one specimen that failed at 4.3 million cycles near the lower grip. The difference between the fatigue limits of the two HPS steels is attributed to the difference in their tensile strength. HPS(HT) has a much lower tensile strength than HPS(LT) (518 MPa and 647 MPa, respectively). As the tests were conducted on polished specimens, a surface roughness correction factor (0.67 for HPS(LT) and 0.75 for HPS(HT) (Dowling 1999)) was applied to obtain the endurance limit of AASHTO (1998) fatigue Category A detail. The stress amplitude endurance limits for both HPS plates are approximately 200 MPa, whereas the corresponding value in the AASHTO design specification is 82.5 MPa (165 MPa if expressed as a stress range). This indicates that HPS may provide a distinct advantage over conventional structural steels in the high cycle fatigue range.

Research programs are currently underway at the University of Alberta and Queen's University to evaluate the benefits of HPS 485W at the fatigue limit state. At the University of Alberta, a comprehensive evaluation of HPS cyclic material properties was carried out that included fully reversed fatigue tests over a broad range of strain amplitudes, an evaluation of the endurance limit, and an assessment of the crack propagation behaviour (Chen et al. 2003). The results of this experimental program led to the following conclusions:

1. The ductility of HPS 485W steel tested under monotonic tension is comparable to the ductility of conventional structural grade steels;
2. One heat of HPS 485W steel used in the test program shows similar upper shelf energy absorption as A7 steel, but has a significantly lower transition temperature;
3. Considerable differences in toughness were observed between different heats of HPS;
4. The crack initiation properties of a higher toughness HPS (HPS(HT)) are not better than those of the lower toughness HPS (HPS(LT)), nor are the fatigue properties of HPS significantly superior to those of low toughness conventional steels at higher strain amplitudes;
5. A comparison of crack propagation properties of HPS and 350WT steel indicates that HPS behaves similarly to conventional grades of structural steel, although it may be marginally superior; and
6. The HPS 485W steel tested provides a significantly higher fatigue endurance limit for the base material alone than conventional structural steels, providing a potential advantage in high cycle fatigue applications, although the few full-scale tests on particular details that have been conducted to date have indicated that this may not translate into a higher endurance limit for welded details.

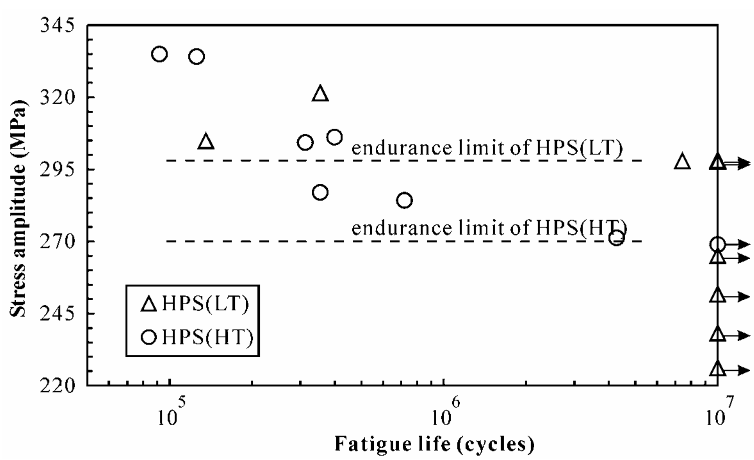
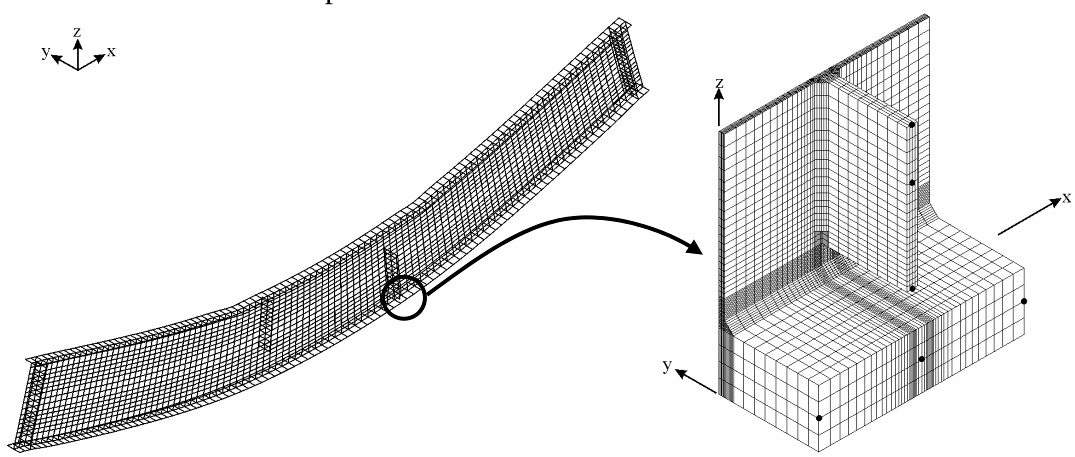
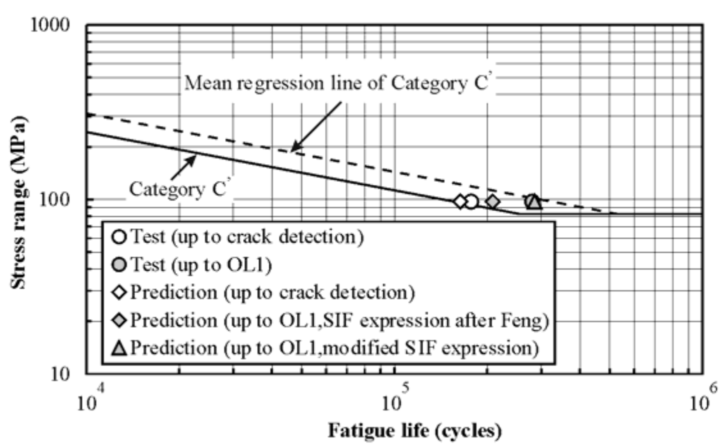


Figure 3 – Endurance limit test results from smooth specimens

Chen *et al*. (2003, 2004) also developed a method to predict the fatigue life of typical details so that the fatigue performance of HPS details can be investigated at minimal experimental effort. The method has been validated using test results on fatigue details of both conventional steels and HPS. A typical example, consisting of a transverse stiffener welded to an HPS steel plate girder (Wright 2003), is illustrated in Figure 4. The localized strains at the critical detail (i.e., the bottom of the stiffener-to-web weld) are determined using a finite element model with a fine mesh (Figure 4(a)). The model is also used to develop stress correction factors needed to implement the fracture mechanics approach in the crack propagation stage. The predicted fatigue life and test results are both presented in Figure 4(b), along with the mean regression and AASHTO (1998) fatigue design curves for this detail. Because the test specimens were periodically overloaded after cracks were detected, the predictions and test results presented in Figure 4(b) are only up to the first overload (OL1). It should also be noted that the stress intensity factor (SIF) needed for fatigue crack propagation calculations was obtained both from expressions proposed by Feng (1996) for a similar detail and from a finite element analysis using the model presented in Figure 4(a) for the specific detail geometry tested by Wright (2003). Excellent agreement between the test results and the predicted fatigue life is observed for this complex detail.



(a) Finite element model of stiffened plate girder and fatigue detail



(b) Fatigue life prediction and test results

Figure 4 – Transverse stiffener detail (Chen *et al.* 2004).

A complementary study is underway at Queen's University to test welded details of HPS 485W to produce data for other categories and applied stress ranges. These tests will be performed on small-scale specimens with welded details that simulate those found on bridge girders. These tests will provide much needed information on the fatigue performance of welded HPS details to supplement the small database of test results in this area.

An important development in Canada is the first HPS 485W bridge, which is planned to be constructed as part of Autoroute Jean-Lesage over the Rivière Henri in Québec by the Ministry of Transport of Quebec. The bridge has a single span of 47.5 m and will be supported by four I-shaped HPS plate girders. The girders will act compositely with a concrete deck reinforced using fiber-reinforced polymer (FRP) bars. The Ministry of Transport of Quebec will use this bridge to gain experience in the design, fabrication, and long-term performance of HPS 485W. It is anticipated that with this experience the frequency of use of HPS for highway bridges in Canada will increase in the near future.

4.0 Summary and Conclusions

New grades of steel, termed “high performance steels,” have been developed in Japan, Europe, and the United States. These steels have higher nominal strengths than conventional steel grades, yet have excellent ductility, toughness, and weldability. HPS 485W was developed in the United States and has now been used in more than 200 bridges. Guide specifications have been published based on this experience.

In Canada, research has focused on the fatigue performance of HPS 485W. Research at the University of Alberta has assessed the fatigue properties of HPS 485W as a material and developed a method of determining analytically the fatigue life of various HPS details. Testing of welded HPS details is currently under way at Queen's University to investigate the potential improvement of the endurance limit with the use of HPS. The fatigue performance of steel bridges is usually governed by fatigue occurring at welded details, so work now underway to assess the fatigue performance of welded HPS 485W is much needed.

5.0 Acknowledgements

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