TOWARDS AN INTEGRATED FRACTURE CONTROL PLAN

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BIOGRAPHY

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Dr. Robert Connor has nearly twenty years of experience in the fatigue and fracture evaluation of steel bridges. He is currently an Associate Professor in the Lyles School of Civil Engineering and Director of the S-BRITE Center at Purdue University. During his career, he has researched fabrication flaws, fatigue cracking, brittle fractures, and developed repair strategies for structures for a variety of agencies including state DOT, rapid transit authorities, construction companies, and structural consultants.

SUMMARY

Significant advances have been made in the understanding of fracture mechanics, material toughness, fatigue crack initiation, fatigue crack growth, fabrication technology, and inspection technology since the inception of the original fracture control plan (FCP) in 1978. Currently, the components of the FCP are divided between independent specifications addressing material, design, fabrication, and inspection independently. Combining each of these aspects of fracture prevention with the advances made since the 1978 FCP a new, integrated FCP can be formed. An integrated FCP has the ability to be reliability-based making fracture no more likely than any other reliability-based limit state; thereby, increasing steel bridge safety while providing an economic benefit to owners though a better allocation of resources.

The following paper discusses the components of an integrated FCP as well as considerations which must be evaluated when forming an integrated FCP. Additionally, an example compares the current material specification to an integrated FCP specification using the integrated approach. A brief discussion on the example results and reliability analysis conclude the paper.

TOWARDS AN INTEGRATED FRACTURE CONTROL PLAN

Objective

First released in 1978, the original AASHTO Fracture Control Plan (FCP) was entitled *1978 AASHTO Guide Specification for Fracture Critical Non-Redundant Steel Bridge Members* (1). The intention of the 1978 FCP was to reduce the likelihood of brittle fracture through a process including design review, material toughness specifications, fabrication requirements, welder certification, and weld inspector qualifications. Through a number of revisions, the components of the FCP were divided into separate specifications designed to address material toughness, design, fabrication, and inspection independently. Design and material requirements are contained in the *AASHTO LRFD Bridge Design Specification* and ASTM A709-13a (2,3). Fabrication and shop inspection requirements are housed in Section 12 of the *AASHTO/AWS D1.5M/D1.5 Bridge Welding Code* (4). In-service inspection requirements are located in the *AASHTO Manual for Bridge Evaluation* (5). As such, currently no single, integrated plan addressing steel bridge fracture exists.

The excellent service record suggests the current approach has been successful in preventing failure due to brittle fracture. However, the FCP was not developed to ensure any specific performance level, crack tolerance versus inspection capability, or overall reliability. Advances in the understanding of fracture mechanics, material and structural behavior, fatigue crack initiation, fatigue crack growth, fabrication technology, and inspection technology have allowed other industries to address fracture in a more integrated manner. Through these advances, it is now possible to create an integrated FCP, combining the original intent of the 1978 FCP, with modern materials, design, fabrication, and inspection methodologies. Further, an integrated FCP will provide an economic benefit to owners by allowing for a better allocation of resources through the use of rational inspection intervals. In summary, an integrated FCP encompassing material, design, fabrication, and inspection can make fracture no more likely than any other limit state; ultimately, allowing for a better allocation of owner resources and increased steel bridge safety.

Considerations

To create an integrated FCP, consideration must be given to several factors. These factors include recognizing defects exist, bridge loading is variable, materials are variable, and both shop and in-service inspection methods have limitations and variability. While each of these realities can be concerning, each can be mitigated through a well-designed, integrated plan. Before discussing the components of an integrated FCP, it is important to understand each consideration and how it will impact the approach.

Flaws exist in all structures no matter the age, location, loading, structure type, etc. Such flaws can be from fabrication or erection, material defects, fatigue crack growth from live load stress, or damage due to an extreme event such as a vehicular impact. The most important consideration for any flaw is the criticality. It must be established if, under the assumed loading conditions and given material properties, the flaw will cause fracture. If the flaw is not determined to be critical, the second most important consideration is how much fatigue life exists before the flaw reaches its critical size. Both of these considerations will be evaluated in detail when discussing the components of an integrated FCP.

Bridges experience a variable loading spectrum ranging from passenger cars to super-heavy loads. As such, it is impossible to predict the exact load a given structure will experience at any moment in time. However, loading can be simplified when considering an integrated FCP. First, cracks grow in fatigue due to live load stress range. Therefore, live load stress range controls crack growth. Second, overloads typically control fracture. The exception to overloads controlling fracture is the case of constraint induced fracture, which is eliminated through proper design and detailing. Simplifying the variable loading spectrum to these two considerations allows it to be incorporated into an integrated FCP.

The fracture toughness data of any steel is highly variable; therefore, material variability must be considered when planning an integrated FCP. Fortunately, work has been performed in other industries to show it is possible to statistically characterize material variability through a concept known as the master curve (6). Further, recent work has been performed on current ASTM A709 HPS as well as historical bridge steels to demonstrate the master curve concept can be applied to the steels commonly used in the bridge industry (7). Statistical characterization of material toughness is an essential part of an integrated FCP because it allows for a reliability-based analysis. Through a reliability analysis the fracture limit state can be treated in design similar to any other reliability-based limit state.

Performing in-depth inspections on highly complex structures comes with a variety of limitations. Examples of such limitations include inspection technique, rigor of inspection method, or limited access, among many others. Regardless of the reason, inspection limitations must be considered when planning an integrated FCP. Recent work has been performed in the areas of setting rational inspection intervals as well as probability of detection (POD) (8). Such studies have not only provided much needed insight into inspection limitations but have created tools to deal with these limitations. Further, understanding inspection from a statistical standpoint allows for in-service inspection to be incorporated into the reliability of an integrated FCP.

The above is a brief discussion of some of the key considerations required to properly develop an integrated FCP. Interestingly, ignoring that defects exist, loads vary, materials vary, and inspection limitations exist, there would be no reason to explore an integrated FCP because bridges would be effectively problem free. However, these considerations are realities; fortunately, each one can be managed through a well-designed, integrated FCP. For example, material is available with high-toughness, capable of tolerating large cracks. Tolerable crack sizes can be calculated using modern fracture mechanics. Statistical methods are available to quantify material variability. Fatigue crack growth calculations are capable of computing fatigue life based on initial crack sizes. POD studies have begun to quantify detectable crack sizes. Rational inspection intervals can be established based on a safe fatigue crack growth life. Leveraging and integrating the results of such research will allow for fracture to be treated as any other reliability-based limit state.

Components of an Integrated FCP

The essence of an integrated FCP is to prevent fracture through a series of checks and balances utilizing interrelated components, with redundancy built into the methodology. The idea of the methodology is if a shortcoming exists in one component it is safely compensated by another. Such a process starts with design and continues through the entire life of a structure. For new steel bridges the required components of an integrated FCP include design considerations, material properties, fabrication guidelines, and in-service inspection. Each component will be discussed in detail in the following subsections. The components will be discussed chronologically of a typical bridge life cycle; however, it is important to remember each component is interrelated and tied to one another. The relationships between the components will also be discussed in the following sections

Design Considerations

An integrated FCP approach needs to be developed and adopted at the outset of design. Early considerations regarding design details and live load stress range can directly impact the success of an integrated FCP. For example, designing a structure to have a low live load stress range and selecting highly fatigue resistant details could effectively eliminate the likelihood of fatigue crack growth during the life of the bridge.

Selecting details with superior fatigue performance is only one aspect of detail selection for an integrated FCP. Equally important is selecting details which simplify fabrication. Complex details increase the probably of fabrication errors which can lead to in-service problems. Lastly, utilizing details which can be easily inspected is also imperative.

Design is the foundation for the integrated FCP. Decisions made during design can directly influence the overall performance of the integrated FCP over the lifespan of a structure.

Material Properties

A subset of design considerations is material selection. The properties of the design material are an imperative part of the integrated FCP. As such, material properties are treated independent of design considerations.

Material properties directly influences the tolerable crack size of a member. Critical flaw size is a byproduct of the fracture toughness of a given material. A material with a low fracture toughness can only withstand small flaws before fracture. Conversely, a material with a high fracture toughness will be able to resist larger flaws before fracture. Tolerable flaw size is directly related to in-service inspection quality; the larger the flaw, the more likely it is to be detected during a routine inspection. As such, when specifying material properties for a structure the designer is actually setting the critical flaw size required to be detected during an in-service inspection. Tying material properties to in-service inspection is fundamentally how the integrated FCP protects against fracture.

Material selection also impacts fabrication as different materials require specific fabrication processes. For example, specifying ASTM A709 high performance steel (HPS) over conventional A709 steel improves weldability by reducing the amount of preheat and post-weld treatment required. Improved weldability reduces the likelihood of defects in the weld metal or heat affected zone, thus improving the overall structure.

Identifying favorable material properties is a key component to the integrated FCP. Most important is selecting a material with adequate fracture toughness. For example, a damage tolerant material would be able to perform its intended function in the presence of a flaw. Additionally, material with good fabrication qualities will also help strengthen the integrated FCP.

Fabrication Guidelines

The current FCP is almost entirely focused on the fabrication of welded steel bridges. In fact, much of the FCP resides in Section 12 of the *AASHTO/AWS D1.5M/D1.5 Bridge Welding Code* (4). Covering everything from weld processes to weld inspection to weld repair, the current FCP provides a necessary foundation for the integrated FCP for welded structures. Through decades of research and experience the current FCP has developed into a refined document. Historically, the current FCP has done a superb job of controlling fracture in steel bridges.

Much of the current FCP can be incorporated into an integrated approach by building upon the strengths of the current plan. For example, the current FCP includes inspection requirements and acceptance criteria for various welds produced during fabrication. At present, the acceptance and rejection criteria are solely based on workmanship with no tie to fatigue crack growth or fracture. An integrated FCP would tie the acceptance and rejection criteria to initial flaw sizes, crack growth rates, and variability in detection of certain inspection technique. In such an approach, the timing of in-service inspection cycles can be rationally established.

In-Service Inspections

Once a bridge has passed through the stages of design, fabrication, and erection, and has been put into service, an integrated FCP continues through in-service inspections. While design considerations, material properties, and fabrication guidelines all try to prevent fracture, in-service inspections can be used when it is not possible to exploit another component of an integrated FCP. For example, if it is not economically feasible to lower the design stress range and finite life must be used in design, the in-service inspection strategy can be tailored to adjust the reliability of the overall approach.

The inspection process can be defined by method, rigor, and interval. Method refers to the type of inspection being performed. Different methods might include visual, dye penetrant, magnetic particle, ultrasonic, or radiography. Rigor refers to the rate at which the method is applied. For example, a welded joint might be inspected 100% visually as well as 20% using magnetic particle inspection. Interval refers to the period of time between inspections. Currently, the maximum in-service inspection interval is mandated as 24 months with 48 months in some special cases. The rigor of this inspection is limited, and may be performed from the ground. However, fracture critical members require a more in-depth inspection, commonly referred to as a hands-on inspection at an interval not to exceed 24 months (5,9). It should be noted, the current method, rigor, and interval of bridge inspections are arbitrary and based on engineering judgement rather than an objective rationale.

An integrated FCP would establish the method, rigor, and interval of an inspection rationally. Using knowledge of the design, loading, environment, detection capabilities, and other characteristics would tie into the type and frequency of the inspection performed. With an integrated approach, the finite resources for inspection, maintenance, and repair are most efficiently appropriated. For example, a brand new bridge designed to the current design code would not be inspected at the same frequency as a structure built before the modern fatigue provisions (8), at least in the early stages of its life.

Further, an integrated FCP would use POD data to establish the reliability of a given inspection as well as to establish detectable flaw sizes. Quantifying inspection reliability is a key to the overall reliability analysis which will ensure fracture is no more likely than any other limit state. Establishing detectable flaw sizes is necessary to tie flaw acceptance criteria to inspection cycles through fatigue crack growth calculations.

An Integrated Approach

To demonstrate how the four primary components of an integrated FCP can be used to control fracture, a demonstration of an integrated approach will be presented. A comparison is made between the current material specification and a damage tolerant material specification. The damage tolerant specification accepts defects, assumed to be cracks, exist in all structures. Through the use of an integrated FCP these defects can be appropriately controlled ensuring fracture is no more likely than another reliability-based limit state. Using an initial assumed defect size, in-service stress range, and crack growth rate, an appropriate inspection interval will be calculated in the example. Following the illustration, a brief discussion compares the results of the two specifications as well as briefly describes how reliability can be tied into the approach.

Material Toughness

ASTM A709 is the current material specification for structural steels used in bridges (3). The fracture critical Charpy V-Notch (CVN) impact provisions are found in Table 9 of the Specification. Required impact values must be satisfied at a given test temperature. The test temperature varies depending on the temperature zone in which the bridge is located. Each zone is based on the lowest anticipated service temperature (LAST) at the location of the bridge: 0 °F for Zone 1, -30 °F for Zone 2, and -60 °F for Zone 3. Specimens are tested at temperatures warmer than the LAST because of the dynamic nature of the CVN impact test versus the quasi-static loading rate of bridge structures. The toughness requirements of the Specification are intended to prevent cracks from initiating brittle factures. To satisfy the requirements of the specification, the average impact energy of three CVN specimens must exceed the specified value. Additionally, the Specification requires a minimum test value for fracture critical components. All three CVN specimens must exceed the minimum value. For purposes of simplification, only the HPS grades will be considered for the example. The required fracture critical CVN values for HPS A709 steels are presented in Table 1.

Table 2 contains damage tolerant CVN impact values for an integrated FCP. (*It should be noted these values are for demonstration purposes only and do not reflect any specific proposed CVN impact energy values*.) To demonstrate the increase in tolerable crack size due to an increased CVN, the required energy was set at 125 ft.-lbs. for all temperature zones at the LAST.

Table 1: Current material CVN impact requirements

CURRENT MATERIAL SPECIFICATION					
Grade	Thickness (in.)	Minimum Test Value Energy (ft.-lb.)	Minimum Average Energy (ft.-lb.)		
			Zone 1	Zone 2	Zone 3
HPS 50 WF	to 4, incl	24	30 @ 10 °F	30 @ 10 °F	30 @ 10 °F
HPS 70 WF	to 4, incl	28	35 @ -10 °F	35 @ -10 °F	35 @ -10 °F
HPS 100 WF	to 2.5, incl	28	35 @ -30 °F	35 @ -40 °F	35 @ -40 °F
	over 2.5 to 4, incl	NA	Not permitted	Not permitted	Not permitted

Table 2: Integrated FCP material CVN impact requirements

INTEGRATED FCP SPECIFICATION					
Grade	Thickness (in.)	Minimum Test Value Energy (ft.-lb.)	Minimum Average Energy (ft.-lb.)		
			Zone 1	Zone 2	Zone 3
Damage Tolerant	TBD	TBD	125 @ 0 °F	125 @ -30 °F	125 @ -60 °F

Numerous conversions exist to relate CVN impact energy to fracture toughness (10). For this work, the methods presented in *BS7910:2013 Guide to Assessing the Acceptability of Flaws in Metallic Structures* was used to estimate fracture toughness (11). The selected procedure includes a size correction for material thickness as well as a five percent statistical tolerance bound on the fracture toughness, meaning there is a 95% probability the toughness will be greater than the estimate. Further, the master curve procedure calculates fracture toughness at a given temperature. As the example Integrated FCP Specification calls for testing to be performed at the service temperature, resulting fracture toughness is consistent regardless of bridge location and corresponding temperature zone. This is a major contrast to the provisions of the current specification. Table 3 presents the resulting Zone III fracture toughness value for each steel grade. The fracture toughness for the current specification is referred to as $K_{specification}$; while, the fracture toughness of the integrated FCP specification is referred to as $K_{DamageTolerant}$.

Table 3: Zone III Fracture toughness

CURRENT MATERIAL SPECIFICATION	
Grade	**$K_{Specification}$ (ksi√in.)**
HPS 50 WF	35
HPS 70 WF	39
HPS 100 WF	46
INTEGRATED FCP SPECIFICATION	
Grade	**$K_{DamageTolerant}$ (ksi√in.)**
Damage Tolerant	122

Tolerable Size

Fracture mechanics allows for the calculation of tolerable crack size based on material toughness. Calculations for the example were performed using closed-form linear elastic fracture mechanics (LEFM) solutions. Using LEFM was a conservative approach because of the ductility inherent in steel. Therefore, the additional plastic contribution available due to strain hardening will be neglected resulting in a conservative, yet reasonable, critical flaw size.

LEFM solutions exist for a wide variety of crack geometries. Two of the most common geometries will be explored for this demonstration: a through-thickness edge crack and a through-thickness center crack. The single-edge notched tension specimen and center cracked tension specimen geometries are presented in Figure 1. It should be noted, standard convention defines an edge crack with length *a*, and a center crack with length *2a*. This designation is followed in the figures, tables, and text of this example; therefore, crack sizes are always presented in terms of total measurable crack length.

Closed-form LEFM solutions for both the edge crack and center crack geometries were taken from *Fundamentals of Structural Integrity* (12). Several parameters were held constant for all calculations. The width and thickness used in the computations were 24 in. and 2 in., respectively. The applied stress for the tolerable crack size calculation was set to 75 percent of material yield, as it reasonably corresponds to the maximum allowable overload (5). Tolerable crack size results are presented in Table 4. Any crack length in Table 4 resulting in yield on the net section is indicated by an asterisks.

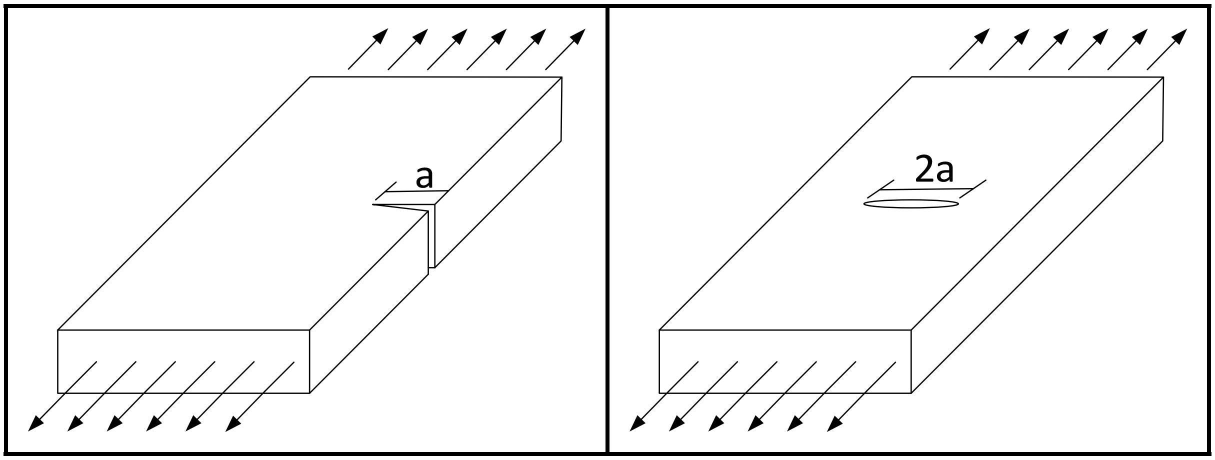

Figure 1: Representative flanges with through-thickness edge and center cracks

Table 4: Tolerable crack sizes

Grade (ksi)	Applied Stress (ksi)	CURRENT MATERIAL SPECIFICATION			INTEGRATED FCP SPECIFICATION		
		$K_{Specification}$ (ksi√in.)	Edge a (in.)	Center 2a (in.)	$K_{DamageTolerant}$ (ksi√in.)	Edge a (in.)	Center 2a (in.)
50	37.5	35	0.23	0.56	122	2.42	6.78*
70	52.5	39	0.14	0.36	122	1.33	3.46
100	75.0	46	0.09	0.24	122	0.67	1.70

Fatigue Life

Fatigue life calculations can be performed to determine the number of cycles to reach a given crack length. Commercial software is available to perform such fatigue crack growth analysis. For the current investigation the software package AFGROW was utilized (13). AFGROW includes an array of built-in common geometries including those investigated in this example. A cycle by cycle analysis determines when an initial flaw grows to a user defined final crack length or results in fracture.

All analyses were performed utilizing the same parameters. A dead load stress equal to 40 percent of the material yield strength was employed for each analysis: 20 ksi, 28 ksi, and 40 ksi for grades 50, 70, and 100, respectively. A constant amplitude stress range of 3 ksi was used for every analysis. Based on field monitoring performed on several in-service structures this was deemed to be realistic and reasonable (14). Thus, the stress range was cycled between the dead load stress and 3ksi above the dead load stress.

AFGROW also allows for the input of material specific crack growth rates. For the comparison, all crack growth rate parameters were assumed to be the same for all analyses. Such parameters included the Paris crack growth rate constant, Paris exponent, and threshold stress intensity. AFGROW contains a built-in material library. For all analyses material parameters from Grade A588 steel plate were used. The only modified parameter to the built-in constants was the threshold stress intensity. The threshold stress intensity was conservatively lowered to 4.5 ksi√in.

Three initial flaw sizes were selected for each geometry. The same set of *a* values were used for both the geometries: 0.0625 in., 0.125 in., 0.25 in. As presented in Figure 1, holding the *a* value constant resulted in twice the measureable crack length for the center crack as compared to the edge crack. Shorter initial flaw lengths were selected for the edge crack because it is a more severe geometry from a fracture mechanics perspective. The selected initial flaw sizes were conservatively assumed to be large compared to what would be expected from a fabrication shop. However, a fracture mechanics-based assessment requires an initial flaw, and the selected sizes are thought to be realistic considering potential defects caused during erection or an extreme event such as an impact. All analyses were performed until the critical flaw length, presented in Table 4, was achieved. As stated, the assumed overload stress was assumed to be 75 percent of the material yield strength. Results from the analysis, presented in terms of millions of cycles, can be found in Table 5.

The analyses resulting in no fatigue growth are indicated by $<\Delta K_{th}$, indicating the stress intensity demand was below the threshold stress intensity. Conversely, the analyses which resulted in immediate failure because the initial flaw size was greater than critical flaw size were indicated by *FAIL*.

Table 5: Fatigue life

Grade (ksi)	CURRENT MATERIAL SPECIFICATION				INTEGRATED FCP SPECIFICATION			
	Edge		Center		Edge		Center	
	Initial a (in.)	Cycles (millions)	Initial 2a (in.)	Cycles (millions)	Initial a (in.)	Cycles (millions)	Initial 2a (in.)	Cycles (millions)
50		$<\Delta K_{th}$		$<\Delta K_{th}$		$<\Delta K_{th}$		$<\Delta K_{th}$
70	0.0625	$<\Delta K_{th}$	0.125	$<\Delta K_{th}$	0.0625	$<\Delta K_{th}$	0.125	$<\Delta K_{th}$
100		$<\Delta K_{th}$		$<\Delta K_{th}$		$<\Delta K_{th}$		$<\Delta K_{th}$
50		30.0		$<\Delta K_{th}$		65.8		$<\Delta K_{th}$
70	0.125	8.8	0.25	$<\Delta K_{th}$	0.125	62.9	0.25	$<\Delta K_{th}$
100		FAIL		$<\Delta K_{th}$		56.7		$<\Delta K_{th}$
50		FAIL		5.0		28.3		47.5
70	0.25	FAIL	0.5	FAIL	0.25	25.4	0.5	43.4
100		FAIL		FAIL		19.3		35.2

Inspection Interval

Using the calculated fatigue life, an inspection interval was tabulated. A few assumptions were required to convert the millions of cycles calculated from the fatigue life to an interval in years. The previously made assumptions about applied overload, stress range, detectable flaw size, and crack growth properties all still remain. In addition, it was assumed the ADTT for the given structure was 1000. An ADTT of 1000 represented over 75% of all bridges in Indiana (15). As such, it is recognized this number does not represent all structures; however, regardless of the actual ADTT, the objective is to show how to set a rational inspection interval. Thus, any value can be used.

For the demonstration, the calculated inspection interval was tabulated from the total fatigue life. When setting an actual inspection interval using the integrated FCP, a reduced interval, for example, 80% of the calculated interval, could be considered for added conservatism. Table 6 presents the number of years for both geometries at each initial flaw size. Analyses in which no crack growth was tabulated because the threshold stress intensity was not exceeded were indicated by *Infinite*. Once again, the analyses resulting in immediate failure were indicated by *FAIL*.

Table 6: Inspection interval

Grade (ksi)	CURRENT MATERIAL SPECIFICATION				INTEGRATED FCP SPECIFICATION			
	Edge		Center		Edge		Center	
	Initial a (in.)	Interval (years)	Initial 2a (in.)	Interval (years)	Initial a (in.)	Interval (years)	Initial 2a (in.)	Interval (years)
50	0.0625	Infinite	0.125	Infinite	0.0625	Infinite	0.125	Infinite
70		Infinite		Infinite		Infinite		Infinite
100		Infinite		Infinite		Infinite		Infinite
50	0.125	82.2	0.25	Infinite	0.125	180.3	0.25	Infinite
70		24.1		Infinite		172.3		Infinite
100		FAIL		Infinite		155.3		Infinite
50	0.25	FAIL	0.5	13.7	0.25	77.5	0.5	130.1
70		FAIL		FAIL		69.6		118.9
100		FAIL		FAIL		52.9		96.4

Discussion

Current versus Integrated Specification

The above example compares the current fracture critical material specification to a damage tolerant specification for an integrated FCP. Each specification was analyzed using the integrated approach. To compare results, Table 7 combines the calculated inspection interval and final crack length for each geometry and each specification. Not all initial crack lengths are included in Table 7. Any initial flaw size resulting in an infinite interval for all grades was omitted from the comparison table. This included the 0.625 in. initial crack length for the edge crack geometry as well as the 0.125 in. and 0.25 in. initial crack lengths for the center crack geometry. Additionally, when the initial crack length would result in immediate failure was indicated by $a_i > a_c$ in Table 7.

First, the calculated inspection interval was compared. For analyses not immediately resulting in fracture, on average the integrated FCP specification resulted in an increase of 100 years of expected life compared with the current specification. Considering all analyses where an interval could be calculated, the current material specification resulted in an average calculated inspection interval of 40 years as compared to 117 years for the integrated FCP specification. The longer calculated inspection intervals associated with the integrated FCP specification allow for a greater factor of safety when comparing the calculated inspection interval to the actual inspection interval. It should be noted, with the integrated approach material toughness specifications can easily be set in order to align with consistent service life design.

Another interesting observation is the number of cases in which immediate failure was predicted based on the current specification. A total of six out of eighteen analyses, or one third, resulted in immediate failure under the current specification. Aside from the analyses removed because an infinite expected life was achieved for all analyses, the grade 100 did not have a single successful analysis resulting in a calculated inspection interval. Further, none of current specification analyses were able to tolerate an initial edge crack of 0.25 in. Conversely, the integrated FCP specification did not have any immediate failure analyses.

When evaluating the final crack lengths, on average the integrated FCP specification could tolerate final crack lengths over nine times larger than the current specification. Crack length ties directly to inspection success through POD. It should be noted, the integrated FCP specification permits detectable crack lengths. Finding a crack less than 0.5 in. using a visual inspection method is difficult. In comparison, even the shortest final crack length for the integrated FCP specification is greater than this length.

Table 7: Comparison of current and integrated FCP specification

Edge Crack					
Grade (ksi)	Initial a (in.)	CURRENT MATERIAL SPECIFICATION		INTEGRATED FCP SPECIFICATION	
		Interval (years)	Final Crack Length (in.)	Interval (years)	Final Crack Length (in.)
50	0.125	82.2	0.23	180.3	2.42
70		24.1	0.14	172.3	1.33
100		FAIL	$a_i > a_c$	155.3	0.67
50	0.25	FAIL	$a_i > a_c$	77.5	2.42
70		FAIL	$a_i > a_c$	69.6	1.33
100		FAIL	$a_i > a_c$	52.9	0.67
Center Crack					
Grade (ksi)	Initial 2a (in.)	CURRENT MATERIAL SPECIFICATION		INTEGRATED FCP SPECIFICATION	
		Interval (years)	Final 2a Crack Length (in.)	Interval (years)	Final 2a Crack Length (in.)
50	0.50	13.7	0.56	130.1	6.78
70		FAIL	$a_i > a_c$	118.9	3.46
100		FAIL	$a_i > a_c$	96.4	1.70

Reliability Discussion

One of the primary advantages of the integrated FCP is the ability to treat fracture in a manner similar to any other limit state. To do so, a reliability analysis is required. Fortunately, combining the advances since the inception of the 1978 FCP with the components of an integrated FCP, it is possible to calculate a probability of failure with a reliability index equal to other reliability-based limit states.

For example, using the master curve allows for tolerance bounds to be placed on material selection. The master curve tolerance bounds can be combined with the likelihood of an initial flaw being of a certain size to grow in fatigue. These probabilities can be combined with POD data. Additionally, the likelihood of an overload producing a stress of 75 percent of yield during a day when the material toughness just meets the specification value can also be considered. Further, the conservatism applied to the actual inspection interval versus the calculated inspection interval also can be considered in the analysis. As can be seen, with an integrated approach the interaction of each parameter and its impact on the overall reliability of structure can be evaluated.

Conclusion/Road Ahead

Advances made since the inception of the 1978 FCP now allow fracture to be treated like any other reliability-based limit state. For such a paradigm shift, fracture must be treated in an integrated fashion. First, it must be recognized and accepted that defects exist, bridge loading is variable, materials are variable, and both shop and in-service inspection methods have limitations. However, the components of an integrated FCP can mitigate these realities. The required components of an integrated FCP include design considerations, material properties, fabrication guidelines, and in-service inspection. An example of the integrated approach was presented comparing the current fracture critical material specification to an integrated FCP specification. The example demonstrated how an integrated approach can result in long critical crack lengths as well as substantially increased inspection intervals.

Looking at the road ahead to an integrated FCP, work is currently underway which will help move closer to the reliability-based fracture approach. Full-scale fracture testing is being performed at Purdue

University to establish CVN requirements for a damage tolerant steel to be used in an integrated FCP material specification. Additionally, inspection reliability is being quantified through POD testing. Future work to move to an integrated approach includes a reliability analysis as well as establishing reasonable initial flaw sizes.

Combining the advances to date, with the current work and future tasks, can revolutionize how fracture is treated in the steel bridge industry. Ultimately, the integrated FCP will increase bridge safety and allow for a better allocation of owner resources.

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