Visual
Abstract

Object-Oriented Software for Fitness-For-Service Assessment of Cracked Cylinder Based on API RP 579

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ABSTRACT. Fitness-for-service assessment of a cracked component intends to evaluate its remaining strength and remaining life to support the implementation of a maintenance plan. This research aims to develop a fitness-for-service assessment software to facilitate the task. The software development process included identifying the software specifications, designing the software structure, manipulating the information in the standard for programming, the graphical user interface design, and finally verification. The assessment procedure employed in this study was the third edition of the standard API RP 579. The software structure was designed using an object-oriented concept. The software can perform integrity assessment levels 1, 2, and 3 option B, leak-before-break assessment, and remaining life assessment for a cracked cylinder that has a through-thickness crack or semi-elliptical surface crack oriented in an axial or circumferential direction. The applied loads could be a nominal axial force, bending moment, and internal pressure, as well as stress profiles perpendicular to the crack plane due to mechanical, thermal, and residual stresses. Accuracy of the software was demonstrated by applying it to example problems. Some aspects of the software extensibility were conceptually discussed.

KEYWORDS. API 579; Fitness-for-Service; Fracture mechanics; Object-Oriented programming; Pressure vessel.

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INTRODUCTION

A crack-like flaw is one of the major service degradation mechanisms for pressure vessels and piping. Fitness-for-service (FFS) assessments are conducted on these cracked components to quantitatively evaluate their suitability for operation and to determine the remaining service life. Numerous professional FFS assessment procedures have been developed worldwide, as reviewed by Hasegawa [1]. To enhance FFS assessment activities, Filiou et al. [2] suggested the development of FFS software. Researchers from universities, organizations, and companies have attempted to develop these software packages [3-14]. The computational basis within these packages may refer to a single specific FFS standard [3, 6, 9, 11, 14], an integration of several FFS standards [12, 13], or a direct implementation of a fracture mechanics methodology without referring to any standard [4, 5, 7, 8, 10].

The API 579 standard [15] is a well-known assessment standard, especially in the petrochemical industry since it covers the major damage mechanisms found in this area of application. Since the first edition was first released in 2000, the code has been continually revised, with the most recent third edition of the code published in 2016. For the crack-like flaw assessment module, the code provides necessary assessment information similar to other well-accepted codes, such as BS 7910, R6, and FITNET procedures. The stress intensity factor (SIF) solutions in the API 579 standard support the broadest range of cylindrical components and allow the calculation of SIF due to an arbitrary stress distribution profile [16]. The latest edition of standard revised a number of elements, for example, the reference temperature for a level 1 assessment, the recommended residual stress profiles, and the method to determine the plasticity correction factor. The FFS software developed based on the API 579 standard is rarely found in the literature [9, 11, 12]. Furthermore, the available software can assess up to level 2 and do not support the latest edition of this standard.

In the development of the FFS software, the extensibility of the software is a necessary concern. Object-oriented (OO) programming is one of the proper approaches that can support the software structure design to satisfy such requirements [17]. A few applications of the OO concept in FFS software for a cracked component were found in the literature [3, 4, 8]. Furthermore, to the authors' knowledge, the OO concept has not yet been applied in the development of a FFS software based on the API 579 standard.

The present paper aims to apply the OO concept to develop the FFS software for a cracked cylinder, based on the latest edition of the API 579 standard. The major concern is to develop a class hierarchy diagram to support the extensibility of the software. The paper is composed of a review of the API 579 standard, the software design process, and an application of the software with example problems.

API 579 STANDARD

The API 579 standard provides three levels of integrity assessment. The higher level of assessment requires more detailed information and analysis, although more precise assessment results can be obtained. Fig. 1 provides an overview of the integrity assessment recommended by the standard. The assessment always starts from level 1 if this level's applicability criteria are satisfied. The higher level of the assessment should be performed if the lower level assessment predicts a component failure. However, if it is decided not to conduct the higher assessment level, the component must be repaired or replaced as suggested by the standard. An assessment of component acceptability must also consider the potential for future component degradation under continued service conditions, based on the potential for crack growth due to fatigue or corrosion. If there is a potential of crack growth, it is necessary to evaluate its remaining life.

The background of the integrity assessment for each level and the remaining life evaluation can be summarized as follows. A level 1 assessment adopts a screening curve approach to determine a permissible crack length in a component. The standard prepares several screening curves according to component geometries (i.e., plate, cylinder, sphere), a crack depth relative to the thickness of the component, and the crack location (i.e., base metal, heat-affected zone, weld). Fig. 2 schematically represents this curve for a particular case. The horizontal axis is $T - T_{ref} + 56$ (in °C), where T is the component service temperature, and T_{ref} is a reference temperature of the material. The T_{ref} can be set as a nil-ductility-transition temperature, RT_{NDT}, or estimated from the specified minimum yield strength (SMYS) and the exemption curve of a material. From knowing the T, T_{ref}, crack depth, crack location, and component wall thickness, the allowable crack length can be determined from this curve. If the allowable crack length is shorter than that from the inspection, the component is predicted to be unsafe.

Level 2 and 3 assessments adopt a failure assessment diagram (FAD) approach. Fig. 3 schematically represents the diagram. The horizontal axis of the FAD is a load ratio based on primary stress, $L_{r,p}$, while the vertical axis is a toughness ratio, K_r. The current status of a cracked component is represented by an assessment point ($L_{r,p}$, K_r). The component is predicted to be safe (or acceptable) only if the assessment point lies on or below the failure assessment curve (FAC). Parameter $L_{r,p}$ is defined as:

$$L_{r,p} = \frac{\sigma_{ref,p}}{\sigma_Y} \tag{1}$$

where $\sigma_{ref,p}$ is the reference stress based on the primary stress, and σ_Y is the yield strength. Equations used to determine the reference stress of a specific cracked component are written in terms of linearized stress components, i.e. the membrane and bending components.
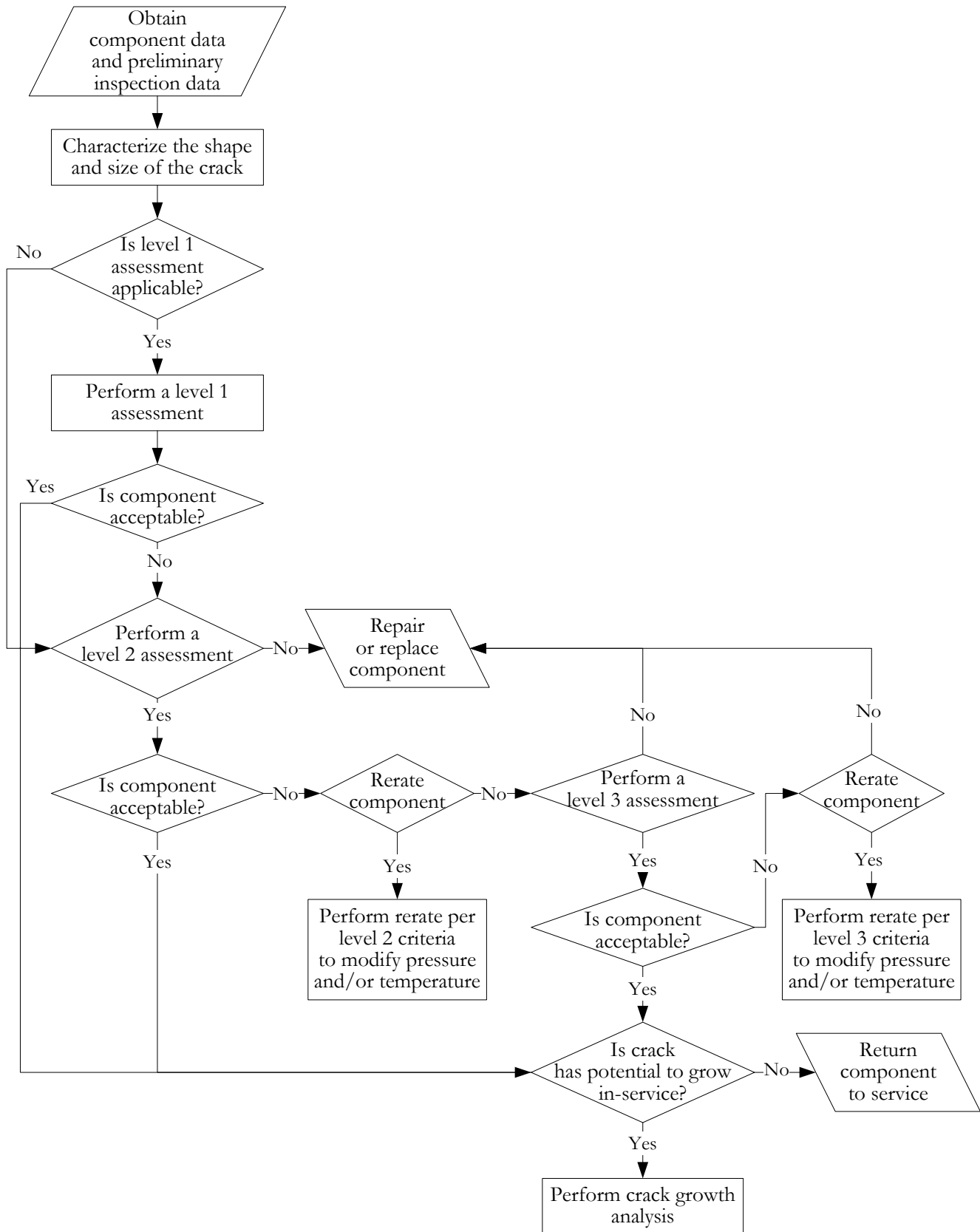
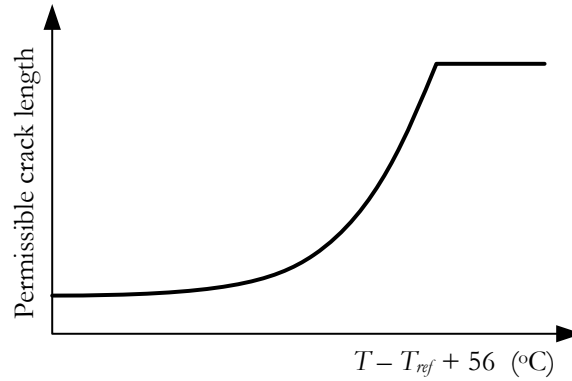Figure 1: Overview of a cracked component assessment based on the API 579 standard.

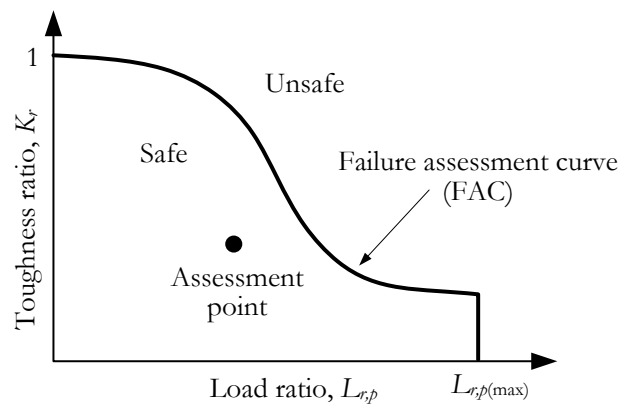Figure 2: Schematic illustration of a screening curve.

Figure 3: Schematic illustration of a failure assessment diagram (FAD).

Parameter K_r is defined as:

$$K_r = \frac{K_{I,p} + \Phi K_{I,sr}}{K_{mat}} \tag{2}$$

where $K_{I,p}$ and $K_{I,sr}$ are mode-I stress intensity factors due to primary and secondary stresses, respectively, K_{mat} is fracture toughness of the component's material, and Φ is the plasticity correction factor. The SIF of specific cracked component geometry and applied loads can be determined from formulas in the standard. The SIF solutions may be expressed in terms of nominal loads, linearized stress components, or influence coefficients. The last form of the SIF solution is appropriate to evaluate the SIF due to a stress profile acting normal to the crack plane, e.g. thermal and residual stress profiles. The standard employs an approximation of the actual stress profile with the following 4th order polynomial function:

$$\sigma(x) = \sigma_0 + \sigma_1 \cdot \frac{x}{t} + \sigma_2 \cdot \left(\frac{x}{t}\right)^2 + \sigma_3 \cdot \left(\frac{x}{t}\right)^3 + \sigma_4 \cdot \left(\frac{x}{t}\right)^4 \tag{3}$$

where σ_0, σ_1, σ_2, σ_3 and σ_4 are best-fit coefficients, t is the nominal thickness corrected with uniform corrosion, and x is the local coordinate pointed along the thickness direction.

A level 2 FAC is a general curve, which means it is independent of the materials and component geometries. This general curve is expressed by:

$$K_r = \left[1 - 0.14\left(L_{r,p}\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(L_{r,p}\right)^6\right]\right\} \tag{4}$$

A level 3 FAC depends on an analysis option. For option B which is implemented in this software, the FAC is expressed by:

$$K_r = \left[\frac{E\varepsilon_{ref}}{L_{r,p}\sigma_Y} + \frac{\left(L_{r,p}\right)^3 \sigma_Y}{2E\varepsilon_{ref}}\right]^{-\frac{1}{2}} \tag{5}$$

where E and ε_{ref} are Young's modulus and reference strain, respectively. It should be noted that the FAC depends on the material properties, so it can be called a material-specific FAC.

The extent of the FAC on the $L_{r,p}$ axis is dependent on a material's deformation behavior. For materials with a yield point plateau (where the strain hardening exponent is greater than 15) or materials with unknown strain-hardening characteristics, the $L_{r,p(\max)}$ is set to 1. For specific material types or classes such as ASTM A508 steel, C-Mn steels, and austenitic stainless steels, the recommended values of $L_{r,p(\max)}$ are 1.15, 1.25, and 1.80, respectively. For materials with a typical strain hardening characteristic, the $L_{r,p(\max)}$ is determined from the following equation:

$$L_{r,p(\max)} = \frac{\sigma_f}{\sigma_Y} \tag{6}$$

where σ_f is the flow stress which is typically an average of the yield and ultimate strength of a material.

If the component is predicted to be safe per level 3 assessment, then the assessment can proceed to evaluate the remaining life of the cracked component. To determine the remaining life, processes of updating the crack size and assessing the integrity of the structure are alternately conducted until the assessment point lies above the FAC, where the component is predicted to be unsafe. The summation of a number of cycles (or time) during each step of crack increment is the remaining life. For the case of a component with a surface crack, both crack length and crack depth are continually evaluated. The surface crack will be recategorized as a through-wall crack when its depth reaches 80% of the wall thickness, as illustrated in Fig. 4. The length of a through-wall crack after recategorized is given by $2c = 2c_s + 2(t - a_s)$, where $2c_s$ and a_s are the length and depth of a surface crack when the crack size meets the recategorization criteria. The component with this through-wall crack is then reassessed. If it is predicted to be safe, the processes of crack growth analysis and integrity assessment will proceed as previously described. Thus, the remaining life of a component with a surface crack might be a combination of the surface crack growth period and the through-wall crack growth period.
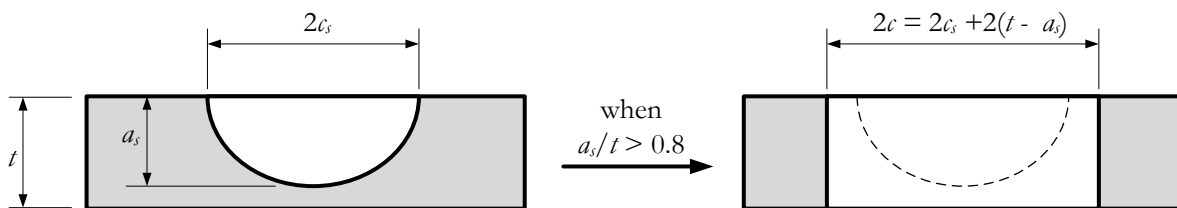

Figure 4: Surface crack recategorized as a through-wall crack.

SOFTWARE DESIGN

This section describes the software design processes, beginning with a description of the software specifications, followed by highlighting some calculation issues. In this study, the information from the standard which is presented in graphical and tabular forms are transformed into other forms to make them more convenient to handle during the programming process. Other issues including calculating the SIF and fatigue crack growth analysis are also addressed. Next, the class hierarchy diagram of the program is presented. Finally, the user interface is demonstrated.

Specifications

The software specifications are related to the types and levels of assessments, cracked component geometries, and types of applied loads. The software was specified to perform integrity, leak-before-break (LBB), and remaining life assessments of a cracked cylinder. Four types of cracked cylinder (namely CTCL, CTCC, CSCLE, and CSCCE) were considered, as illustrated in Fig. 5. For CSCLE and CSCCE, both the inner-wall and outer-wall cracks were included in the study. The treatments of crack interaction and weld strength mismatch were not included. The SI unit system was adopted.

The integrity assessment covered levels 1, 2, and 3 option B. The LBB assessment was permitted for the level 2 and 3 assessments, whereas the remaining life assessment permitted only a level 3 assessment. For the LBB assessment, the user must provide the length of a through-wall crack at a detectable leak rate. The remaining life assessment covered only the crack growth mechanism by fatigue. Furthermore, only cyclically nominal loads with a constant amplitude were considered. The analysis was performed at two representative locations on the crack front.

The applied loads on the cylinder could be nominal loads, i.e. internal pressure, axial force, and bending moment, as well as through-thickness mechanical, thermal, and residual stress distribution perpendicular to the crack plane. These stress profiles are expressed in the form of Eqn. (3), where the coefficients in the equation are specified for given types and directions of stresses. The coefficients of thermal stress profiles were provided by the user. Meanwhile, for residual stress, the user has a choice of whether to use the recommended profiles in the standard.
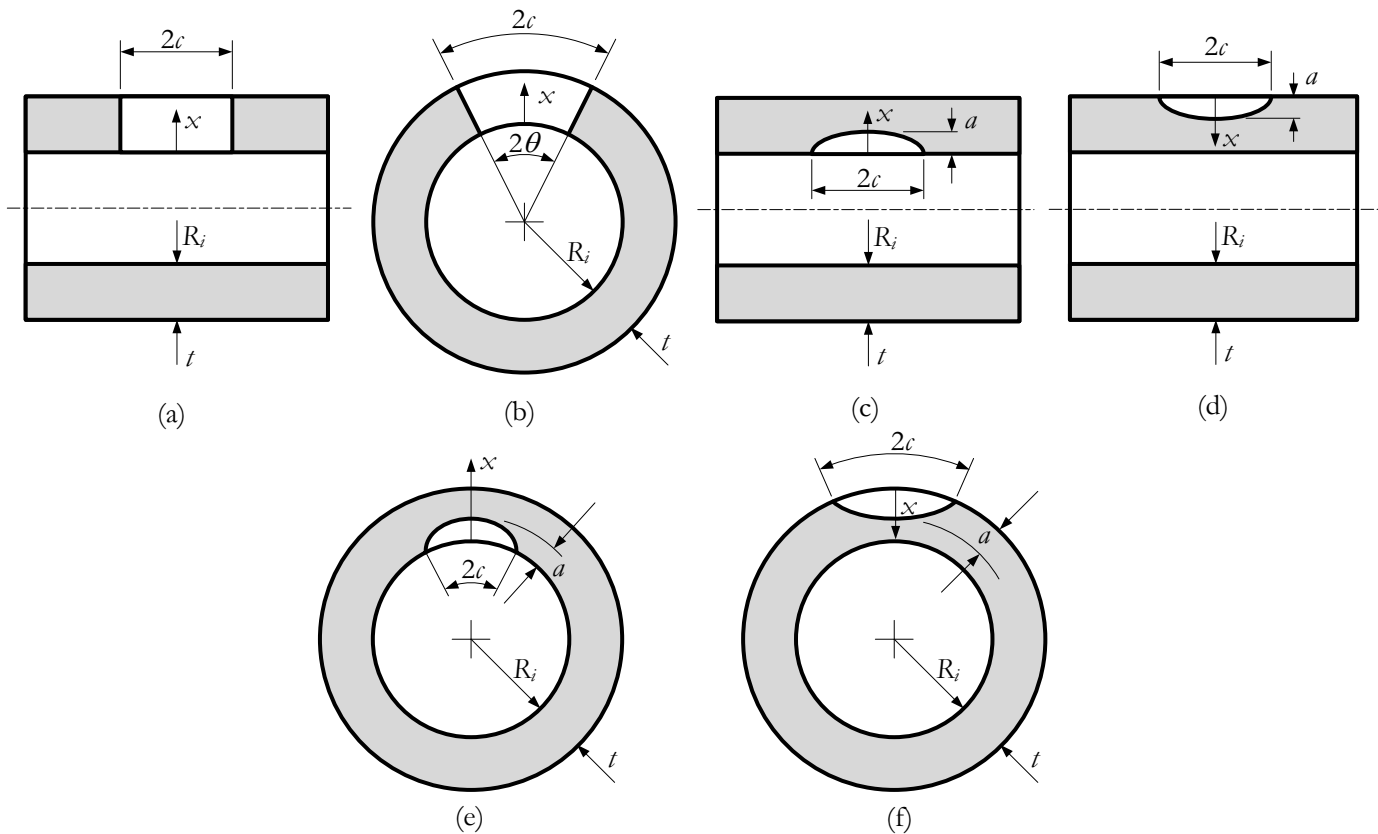

Figure 5: Types of cracked cylinder included in the software: (a) CTCL; (b) CTCC; (c) CSCLE (inner-wall crack); (d) CSCLE (outer-wall crack); (e) CSCCE (inner-wall crack); and (f) CSCCE (outer-wall crack).

The software incorporated a text file containing a material information of some pressure vessel steels. The information includes material specifications, specified minimum yield strength (SMYS), and specified minimum ultimate strength (SMTS). However, the software allowed the user to input actual material information. The constitutive equation incorporated in the software was only the Ramberg-Osgood (R-O) model. The parameters of the R-O model can be user-defined input or estimated by the formulas in the standard. The fracture toughness could be the custom input value or estimation from various methodologies in Tab. 1. The supported fatigue crack growth rate (FCGR) models were Paris and Walker models, with the material parameters being user provided.

Methodology	Region	Model	Reference temperature
Lower bound	Transition	ASME Section XI	Nil-ductility transition temperature, RT_{NDT}
		ASME Section VIII	Estimate from Charpy transition curve and ASME exemption curve
Charpy impact	Transition	Charpy V-notch transition curve	-
	Upper shelf	Rolfe-Novak correlation	-
		Wallin J-integral correlation	-
Master curve	Transition	-	Master curve index temperature, T_0

Table 1: Fracture toughness estimation methodologies adopted in software development.

Calculation issues

The standard provides definite steps to manipulate the input information for each type and level of assessment. Yet some issues require preparation and consideration before coding. The first issue was information preparation in the standard which appears as a graph (e.g., screening curve) or table and converting that into a suitable format for programming. The next issue was the SIF calculation when the origin of the local coordinate on the thickness direction of a cracked cylinder differs from the recommended residual stress profile, or from after crack recategorization. The final issue was related to fatigue crack growth analysis.

Each screening curve was digitized and the coordinates obtained were stored in a text file. An array-type variable was prepared to store the data read from the opened text file while the program was running. A one-dimensional linear interpolation algorithm was used to determine a permissible crack length at an intermediate value of the independent variable, i.e. $T - T_{ref} + 56$. The information from each table was stored in a text file. A one or three-dimensional linear interpolation algorithm was employed depending on the number of independent variables.

The next issue was SIF calculation. Considering the CSCLE and CSCCE cracked cylinders with an external surface crack, shown respectively in Figs. 5(d) and 5(f), the origin of the local coordinate x was defined at the outer wall, whereas the recommended residual stress profiles were typically defined at the inner wall. Therefore, before computing the SIF of these two cracked cylinder geometries, the recommended residual stress profiles must be rewritten in the form of:

$$\sigma(x) = \sigma_0 + \sigma_1 \cdot \left(1 - \frac{x}{t}\right) + \sigma_2 \cdot \left(1 - \frac{x}{t}\right)^2 + \sigma_3 \cdot \left(1 - \frac{x}{t}\right)^3 + \sigma_4 \cdot \left(1 - \frac{x}{t}\right)^4 \tag{7}$$

where σ_0, σ_1, σ_2, σ_3 and σ_4 are recommended coefficients given in the standard. A similar situation occurs when the CSCLE and CSCCE cracked cylinders with an external surface crack (Figs. 5(d) and 5(f)), are respectively recategorized as the CTCL (Fig. 5(a)) and CTCC (Fig. 5(b)) cracked cylinders. The user-defined stress profiles of any type (i.e. mechanical, thermal and residual) for the cases of CSCLE and CSCCE must be rewritten in the form of Eqn. (7) before computing the SIF for the CTCL and CTCC cases.

For fatigue crack growth analysis, the standard does not provide guidance to incorporate the influence of residual stress on the FCGR. This software considered the residual stress as mean stress, thus the stress ratio, R in the Walker FCGR model was given by:

$$R = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}} \tag{8}$$

where $K_{\min}$ and $K_{\max}$ are the minimum and maximum of mode-I SIF due to a cyclic nominal load, respectively. K_{res} is mode-I SIF due to residual stress.

A further consideration for crack growth analysis is the calculation of the remaining life of a cracked cylinder. As a compromise between accuracy and computational time, FCGR was calculated only at the representative locations on the crack front. In addition, the crack size was updated every allowable number of loading cycles, i.e. the FCGR was supposed to be constant during this interval. Herein, the allowable number of loading cycles was set to the number of cycles required to grow the crack by 1% of its previous dimensions.

For a through-thickness crack, FCGRs were calculated at the inner and outer points on the crack front. The allowable number of loading cycles ΔN_{allow} was determined from:

$$\Delta N_{allow} = \text{floor}\left[\frac{\Delta c_{allow}}{\max\left[\left(dc/dN\right)_{in}, \left(dc/dN\right)_{out}\right]}\right] \tag{9}$$

where Δc_{allow} is the allowable increment of half crack length (i.e. $0.01c$), and $(dc/dN)_{in}$ and $(dc/dN)_{out}$ are the FCGRs at the inner and outer points, respectively. Note that Eqn. (9) yields a conservative value of ΔN_{allow} since the maximum between FCGRs at two locations and the floor function were used. The increments of a half crack length at the inner point Δc_{in} and the outer point Δc_{out} under a cyclic load of ΔN_{allow} cycles are $\Delta c_{in} = \Delta N_{allow} \cdot (dc/dN)_{in}$ and $\Delta c_{out} = \Delta N_{allow} \cdot (dc/dN)_{out}$, respectively. Since Δc_{in} is typically unequal to Δc_{out} (Fig. 6), the maximum between both values was chosen to be the half crack length increment Δc, i.e. $\Delta c = \max(\Delta c_{in}, \Delta c_{out})$.

For a semi-elliptical surface crack, FCGRs at the surface and deepest points were calculated. The conservative allowable number of loading cycles ΔN_{allow} was determined from:

$$\Delta N_{allow} = \text{floor}\left[\frac{\min\left(\Delta c_{allow}, \Delta a_{allow}\right)}{\max\left(dc/dN, da/dN\right)}\right] \tag{10}$$

where Δc_{allow} is the allowable increment of half crack length (i.e. $0.01c$), Δa_{allow} is the allowable increment of crack depth (i.e. $0.01a$); dc/dN and da/dN are FCGRs at the surface and deepest points, respectively. The increments of half crack length Δc and the increment of crack depth Δa after ΔN_{allow} loading cycles were respectively expressed as:

$$\Delta c = \Delta N_{allow} \cdot dc/dN, \text{ and } \Delta a = \Delta N_{allow} \cdot da/dN \tag{11}$$

Class hierarchy diagram

This section explains the class hierarchy diagram development process. This process involved identifying appropriate classes and assigning class relationships. This research identified the classes from nouns and noun phrases in the problem description. The following paragraph presents the problem description and the candidate classes are underlined.

In-servicing <u>cylindrical vessel</u> has been degraded by <u>uniform corrosion</u> and <u>crack</u>. To perform an <u>assessment</u>, engineers gather information which is a fabrication (e.g., <u>weldment</u> and <u>residual stress</u>), <u>material</u> (e.g., <u>general information</u>, <u>tensile properties</u>, <u>fracture toughness</u>, <u>fatigue crack growth rate</u>), <u>environment</u>, <u>nominal loads</u>, and <u>stresses</u> on the crack plane.

For convenience, these identified classes are renamed and listed (in the same order as those appearing in the problem description) as *Cylinder*, *UniformCorrosion*, *Crack*, *Assessment*, *Weldment*, *ResidualStress*, *Material*, *GeneralInfo*, *Tensile*, *Toughness*, *FCG*, *Environment*, *NominalLoad*, and *Stress* classes.
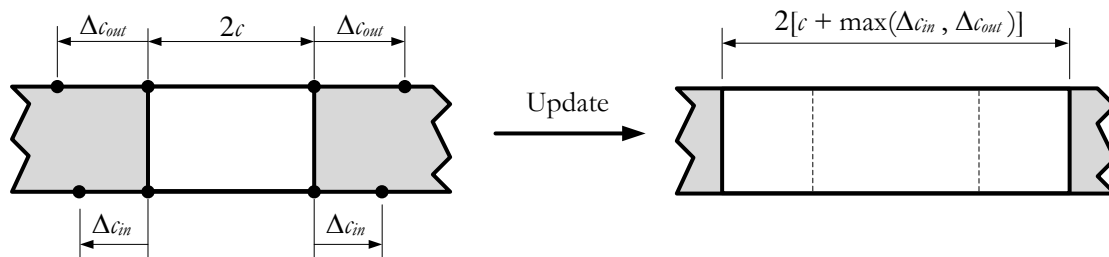

Figure 6: Crack length updated for through-wall crack growth analysis.

The class hierarchy was developed by applying the concepts of association, inheritance (the "is a" relationship), and composition (the "has a" relationship). The concept of inheritance might introduce generalized classes. The class diagram obtained from these considerations is shown in Fig. 7. Brief explanations of the diagram are given as follows:

- The *GeneralInfo*, *Environment*, and *NominalLoad* classes were changed to be the property (also called attribute) of the *Material*, *Structure*, and *Cylinder* classes, respectively. They are therefore not included in the diagram.
- The *UniformCorrosion* and *Crack* classes are derived from the same base class (the *Defect* class) since both uniform corrosion and crack are specific types of defects.

- The *Cylinder* class is derived from a more generalized class (the *Structure* class) since a cylinder is a specific type of structure. This class had a specific method to calculate the stresses due to nominal loads.
- The *Structure* class is an aggregation of the *Weldment* and *Defect* classes because weldment and defect might exist in a structure. This class was also composed of the *Material* and *Stress* classes since a structure is made of a specific type of material and is always under stress.
- The *ResidualStress* class is derived from the *Stress* class because residual stress is a specific type of stress. The *Stress* class had a method to determine linearized stress components.
- The *Weldment* class is composed of the *Material* and *ResidualStress* classes because weldment is made of a specific type of material and always introduces residual stress in a structure.
- The *FCG* class is derived from the *CrackGrowth* class since fatigue crack growth is a specific type of crack growth mechanism.
- The *Material* class is composed of the *Tensile*, *Toughness*, and *CrackGrowth* classes.
- The *Assessment* class is associated with the *Structure* class because assessment requires information of structure to perform calculations.

By considering the software specifications and its extensibility, modifications were made to the *Structure*, *Stress*, *Tensile*, *Toughness*, *CrackGrowth*, and *Assessment* classes, as shown respectively in Figs. 8(a) – 8(f), where the new classes are presented in shaded rectangles. Descriptions of these modifications, important properties, and methods of the classes are summarized below:

- In Fig. 8(a), the *CrackCylinder* class is derived from the *Cylinder* class. The important properties of the *CrackCylinder* class were crack information, SIF and reference stress. The *CrackCylinder* class also used the properties of the ancestor classes (i.e. *Cylinder* and *Structure* classes) such as cylinder dimensions and the amount of uniform metal loss. This class is a base class of the *CTCL*, *CTCC*, *CSCLE*, and *CSCCE* classes, where each subclass has specific methods to calculate SIF and reference stress.
- The class hierarchies in Figs. 8(b) to 8(d) are the player-role pattern in OO design. The player classes *ResidualStress*, *Tensile*, and *Toughness* are composed of the role classes *ResidualModel*, *Constitutive*, and *KIcEstModel*, respectively. Various subclasses of the role class allow behaviors of a role class's object to vary according to the subclass's object being created.
- In Fig. 8(b), the *ResidualModel* class had the coefficients of residual stress profile as a property. The derived class, i.e. *ResStrCylinder*, had a specific method to determine these coefficients of a cylinder from the weld information.
- In Fig. 8(c), the abstract class *Constitutive* had only a name of the stress-strain relation as a property. The derived class *RambergOsgood* had material parameters of the R-O model as a property and the class had a method to compute a strain from a given stress. The derived class *RambergOsgoodEst* added a specific method to estimate the material parameters of the R-O model from specified tensile strengths.
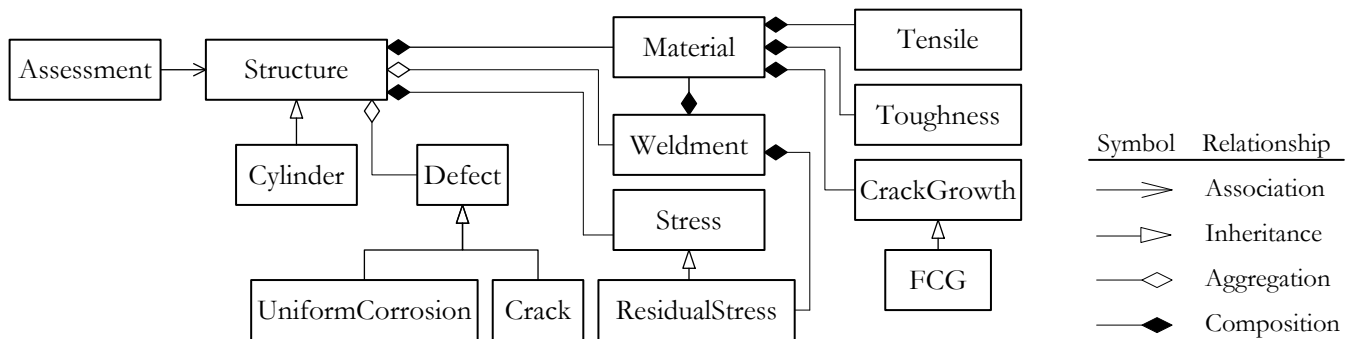

Figure 7: Preliminary class diagram derived from candidate classes.

- In Fig. 8(d), the *Toughness* class had K_{mat} as a property. Each of the derived classes *ASME*, *Charpy*, and *MasterCurve* had a method to estimate a K_{mat} according to ASME section XI lower bound curve, Charpy impact transition curve or Charpy impact energy, and master curve methodologies, respectively.
- In Fig. 8(e), the abstract class *FCG* has two subclasses named *Paris* and *Walker*. Each subclass had parameters in FCGR model as a property and was able to calculate the fatigue crack growth rate.

- In Fig. 8(f), the *AssessCrack* class is derived from the abstract class *Assessment*. This class had a method to perform an assessment of a cracked cylinder according to the specified type and level of assessment. The object created by the abstract class *Level* behaves according to the object of the subclass being created, i.e. the *Level1* or *Level2* class. The *Level1* class had a method to determine a permissible crack length from a screening curve. The *Level2* class had a method to determine an assessment point and the FAC. The *level3* class inherits the method to determine an assessment point from the *Level2* class and overrides the method to determine the FAC.
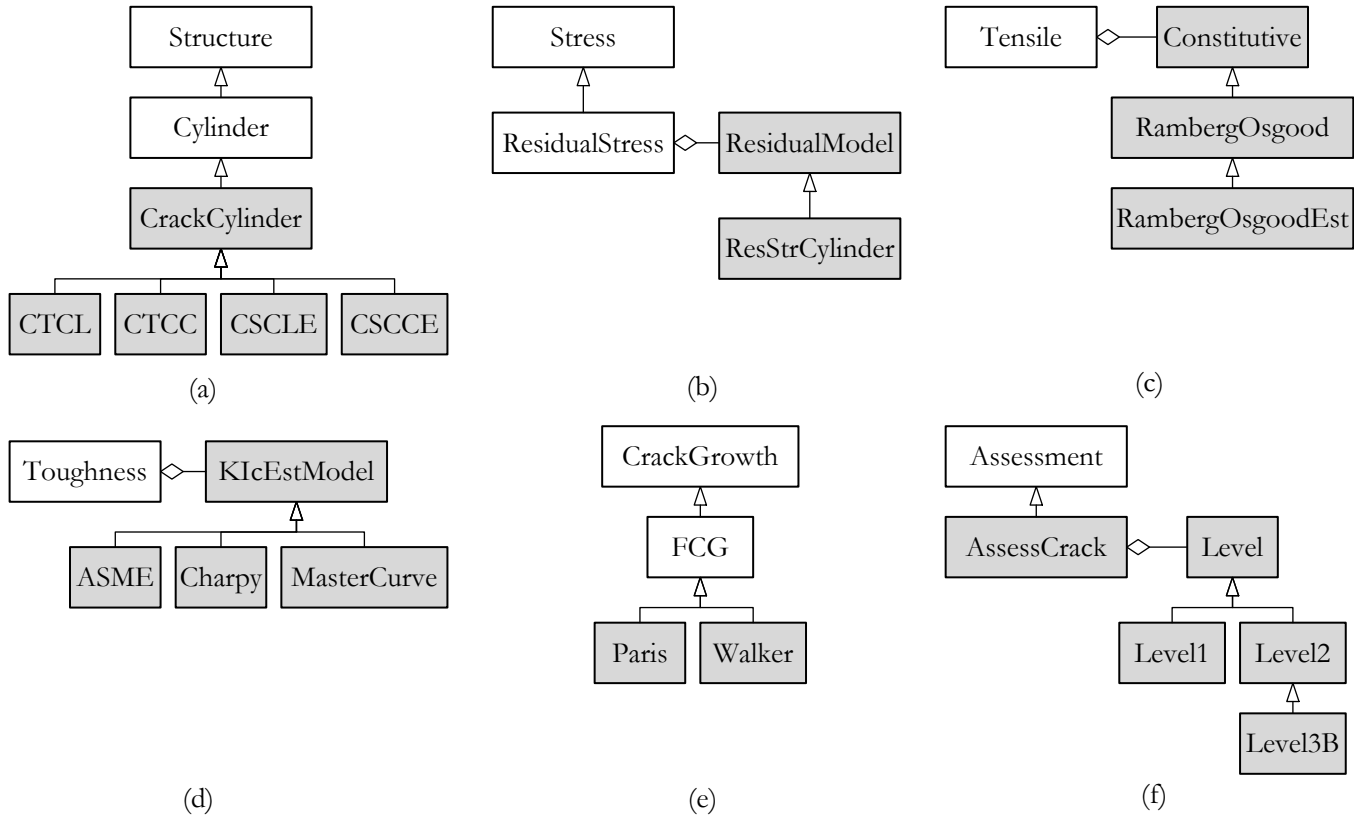
Figure 8: Class refinement in the preliminary class diagram (Fig. 7). The additional classes are shown in shaded rectangles: (a) *Structure* class; (b) *Stress* class; (c) *Tensile* class; (d) *Toughness* class; (e) *CrackGrowth* class; and (f) *Assessment* class.

All classes shown in Figs. 7 and 8 are classified as the application classes. To complete the software design, it is necessary to create the graphical user interface (GUI) classes. The GUI classes have the purpose of receiving input information and creating and managing the application objects. The designed GUI class hierarchy and its communications with the application classes (partially presented) are illustrated in Fig. 9. All the GUI classes in this figure have a name starting with the letters "frm". The *frmMain* class creates the application objects of the *Structure* and *Material* classes. After that, it creates the GUI object (or windows) of the *frmCrackCylinder* class to acquire information about cylinder geometry, welding, crack, and applied loads, and it also creates the GUI object of the *frmMaterial* class to acquire information about materials. The acquired information is then assigned to the corresponding application objects. Finally, the *frmMain* class creates the object of the *Assessment* class to assess the object(s) of the *Structure* class.

At this stage, the present class diagram can fulfill the software specifications. However, it may be useful to reexamine the present class diagram for its extensibility. The following paragraph conceptually discusses an extension of the software if it is required to include the other types of a cracked component.

Fig. 10 shows an extension of the class diagram to incorporate the other cracked component types, e.g. a cracked plate. The *Plate* and *ResStrPlate* classes are derived from the *Structure* and *ResidualModel* classes, respectively. The *Plate* class has the plate dimensions (e.g., width and thickness) as properties and has a method to calculate for calculating nominal stress. The *CrackPlate* class which is derived from the *Plate* class has the SIF and reference stress as properties. Additional classes for a specific type of cracked plate can be derived from the *CrackPlate* class. Each of the inherited classes has a specific method to calculate SIF and reference stress. The derived class *ResStrPlate* has a specific method to determine the residual

stress profile of a plate from the weld information. In summary, the present class diagram has sufficient flexibility for further additional functions and improvements.
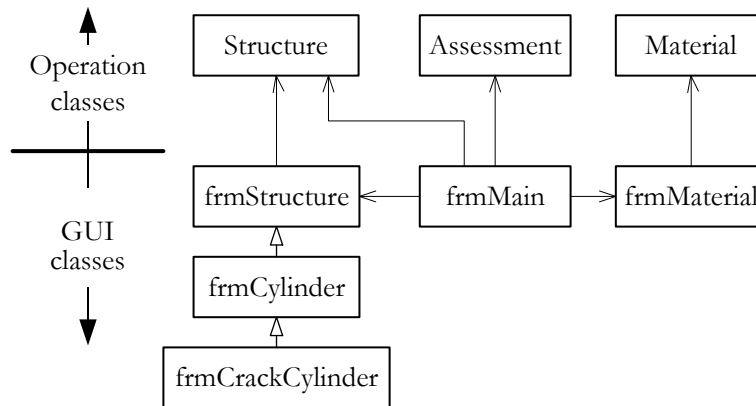

Figure 9: Class diagram of the graphical user interface (GUI) classes and their association with the application classes.

User interface

The implementation of GUI design and programming was accomplished by using the integrated development environment (IDE) of Delphi 10.2.3 community edition from Embarcadero Technologies. The information for the assessment was organized into three windows: *Main* window (Fig. 11); *Cracked Cylinder* window (Figs. 12 and 13); and *Material* window (Fig. 14). Note that the displayed information in all of these figures is for the level 3 option B assessment. For the lower assessment level, unnecessary information will be hidden or disabled. Instructions for using the software are described as follows.

First, the defect type and assessment level in *Option* tab of *Main* window (Fig. 11(a)) are specified. If a level 2 or 3 option B assessment is selected, the additional options for assessment will be enabled. For the LBB assessment, the user must input the crack length at the detectable leak rate. The remaining life assessment is enabled for the level 3 option B assessment and the user must specify the crack growth mechanism.
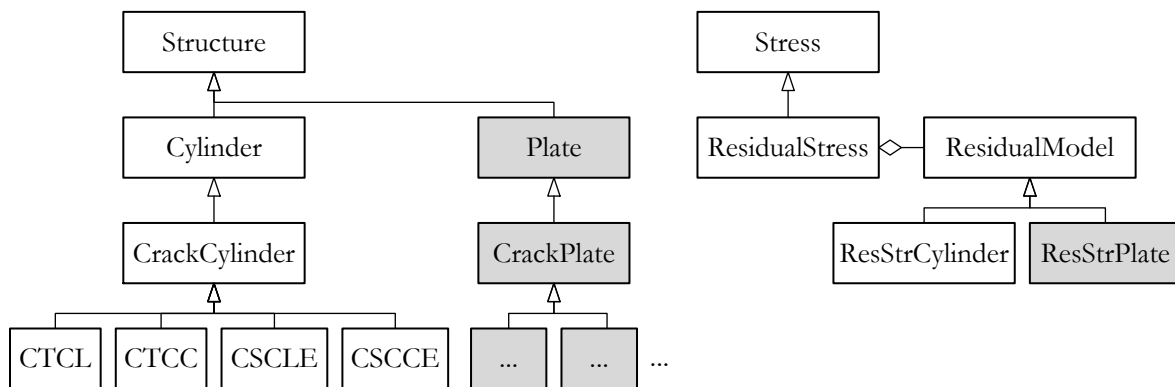
Figure 10: Extension of the application classes to incorporate a cracked plate assessment.

Next, it proceeds to the *Information* tab of the *Main* window (Fig. 11(b)) where the user is asked for specifying equipment details and material data source. The user then opens the *Cracked Cylinder* window (Figs. 12 and 13) and *Material* window (Fig. 14) to specify detailed information of the cracked cylinder and material properties, respectively.

The *Cracked Cylinder* window organizes information into *Dimension*, *Weldment*, *Defect*, and *Operation* tabs, as shown in Figs. 12(a) to 12(d), respectively. The *Operation* tab covers information about design, service, and maintenance of the cylinder. Additional details of the service conditions are illustrated in Fig. 13. For the *Mechanical load* tab shown in Fig. 13(a), the user can specify the applied nominal loads or coefficients of a stress profile. The *Thermal stress* tab is similar to the

Mechanical load tab so it is not presented. For the *Residual stress* tab shown in Fig. 13(b), the user can enter the coefficients of a residual stress profile or allow the software to select the recommended profile in the standard.

The *Material* window has two main tabs to specify properties of base material and weld material (if weldment exists). Both tabs contain almost similar information, so only *Base material* tab is presented (Fig. 14). The mechanical properties are organized into tabs of *Tensile*, *Fracture toughness*, and *Crack growth*, with details of each tab shown in Fig. 14(a) - (c), respectively.

The user can perform an assessment after completing the information and analysis options. The result of each assessment type or level is separately saved in a text file that can be displayed in the *Result* tab of the *Main* window (Fig. 11(c)).
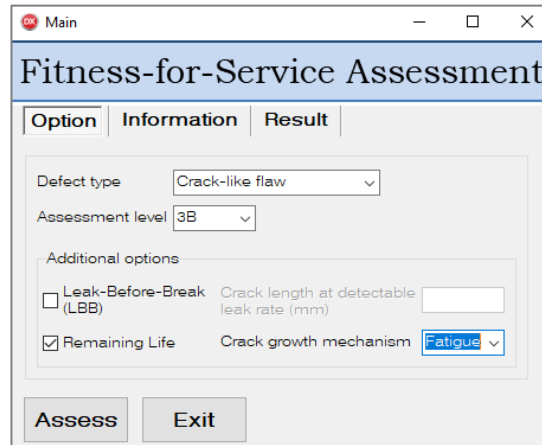
(a)
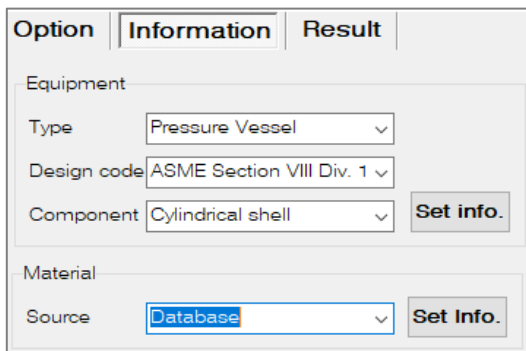
(b)
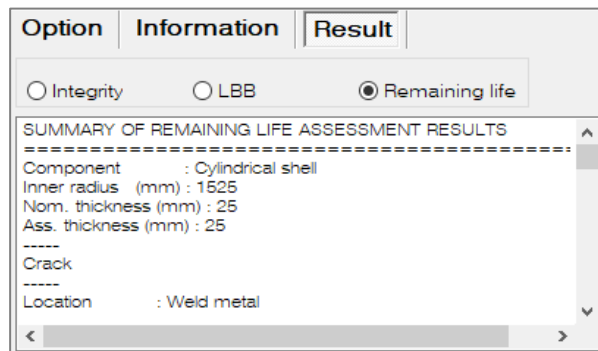
(c)

Figure 11: *Main* window: (a) *Option* tab; (b) *Information* tab; and (c) *Result* tab.
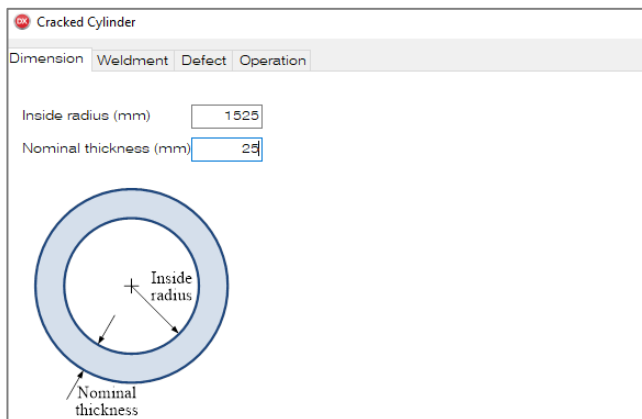
(a)
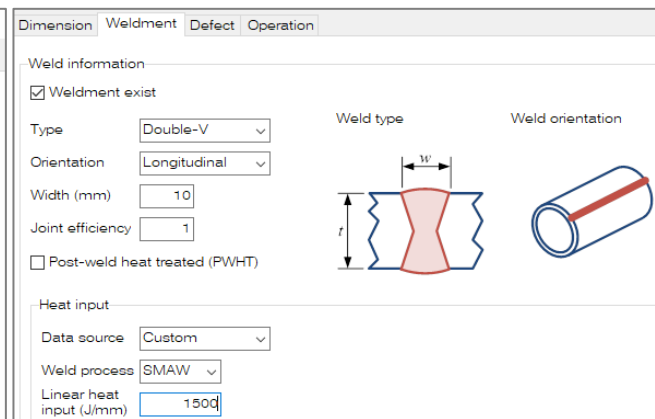
(b)

Figure 12: *Cracked cylinder* window: (a) *Dimension* tab; (b) *Weldment* tab; (c) *Defect* tab; and (d) *Operation* tab.

(c)

(d)

Figure 12 (continued): *Cracked cylinder* window: (a) *Dimension* tab; (b) *Weldment* tab; (c) *Defect* tab; and (d) *Operation* tab.
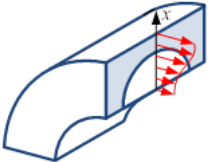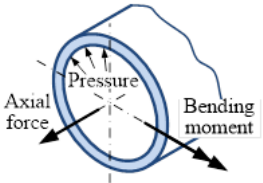

(a)

(b)

Figure 13: Service load (or stress): (a) *Mechanical load* tab and (b) *Residual stress* tab.

Material — □

Base material Weld material

Information

Specification No.	SA-516
Type/Grade	70
Nominal composition	Carbon steel
Product form	Plate
Condition	
Size/Thickness (mm)	
P-No.	1
Group No.	2
Exemption curve	B

Mechanical properties

Tensile Fracture toughness Crack growth

Strength

Option	Minimum specified
Yield strength (MPa)	260
Ultimate strength (MPa)	485
Allowable stress (MPa)	138

Deformation

Young modulus (GPa)	200
Poisson ratio	0.3
Constitutive model	Ramberg-Osgood

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{H_{RO}}\right)^{1/n_{RO}}$$

Material parameters	Estimate
H RO (MPa)	
n RO	

(a)

Tensile Fracture toughness Crack growth

Option [Estimate] Estimate model [ASME Section XI]

(Mode I) Fracture toughness (MPa*m^0.5) [ ]

ASME Section XI

Reference temperature [Exemption curve]

RT NDT (deg. C) [ ]

(b)

Tensile Fracture toughness Crack growth

Mechanism [Fatigue]

Fatigue

Model [Paris]

☐ Threshold SIF range (MPa*m^0.5) [0]

Paris Walker

C (mm/cycle) [.000000029]

n [3]

$$\frac{da}{dN} = C(\Delta K)^n$$

(c)

Figure 14: *Material* window: (a) Material information and *Tensile* tab; (b) *Fracture toughness* tab; and (c) *Crack growth* tab.

VERIFICATIONS

This section presents an application of the software to two example problems. The accuracy of the results were investigated by comparing them with results calculated by MathCAD Prime 4 software which performed the same calculation steps. Tab. 2 lists the options of input information for these examples. Descriptions of the examples are given in the following sections.

Input information		Selected options	
		Example 1	Example 2
Weldment (Fig. 12(b))	Heat input data source	Custom	API 579
Residual stress (Fig. 13(b))	Data source	API 579 (2016)	Custom
Tensile (Fig. 14(a))	Strength Option	Minimum specified	Minimum specified
	Material parameters	Estimate	Estimate
Fracture toughness (Fig. 14b)	Option	Estimate	Actual
	Estimate model	ASME Section XI	-
	Reference temperature	Exemption curve	-
Crack growth (Fig. 14c)	Model	Paris	Paris

Table 2: Input information options in the software to solve the example problems.

Example 1

The cylindrical vessel constructed according to the ASME B&PV code, Section VIII Division 1 had a longitudinal semi-elliptical surface crack in the longitudinal seam on the inner wall (i.e. case in Fig. 5(c)). Uniform corrosion was not detected on either the inner or outer walls. The vessel was made of SA-516 Grade 70 steel with a specified minimum yield strength and ultimate strength of 260 MPa and 485 MPa, respectively. The material's exemption curve was assigned as a B-curve. The weld seam was a double V-groove 10 mm wide, produced by a shield metal arc weld (SMAW) process with a linear heat input of 1,500 J/mm and was not subjected to a post-weld heat treatment. The nominal inside diameter and thickness of the vessel were 3,050 mm and 25 mm, respectively. The vessel operated at an internal pressure of 0.7 MPa at 5 °C. An 80 mm long and 5 mm deep crack was detected by ultrasonic and magnetic particle techniques, respectively. The nearest major discontinuity was 800 mm from the crack. The vessel was also subjected to cyclic pressure with a maximum value of 0.7 MPa and a minimum value of 0 MPa. Thus, crack propagation by fatigue was possible. The FCGR is given by $da/dN = 2.9 \times 10^{-8} \Delta K^3$, where da/dN is the fatigue crack growth rate (in mm/cycle) and ΔK is the stress intensity factor range (in MPa·m$^{1/2}$).

In the level 1 integrity assessment, the software used information about the crack size, crack orientation, weld orientation, material's exemption curve, SMYS, and the service temperature. The permissible crack length in the cylinder was determined to be 8.3 mm, smaller than the 80 mm long crack found during the inspection, so the cylinder was predicted to be unsafe.

For the level 2 and 3 option B integrity assessments, the software reported important parameters which are shown in column 2 of Tab. 3, and predicted that the cylinder was safe.

For the remaining life evaluation, the fatigue crack growth rate was the additional input data. The FCGR model selected was Paris's model. The surface crack was recategorized as a through-wall crack that was 99.841 mm long at cycle number 583,672. The cylinder with this through-wall crack was assessed and the software predicted the component was unsafe. Thus, the remaining life reported was 583,672 cycles and a critical crack length and depth were 19.932 and 89.706 mm, respectively, which is the crack size just before recategorization. The remaining life was determined in less than one second of computational time. Both the integrity and remaining life assessment results from this software matched those computed by the MathCAD worksheet.

Example 2

The cylindrical vessel constructed according to the ASME B&PV code, Section VIII Division 1 had a circumferential semi-elliptical surface crack in the circumferential seam on the outer wall (see the case in Fig. 5(f)). Uniform corrosion was not detected on either the inner or outer walls. The vessel was made of SA-106 Grade B steel with a specified minimum

yield strength of 240 MPa and an ultimate strength of 415 MPa, while the fracture toughness was 100 MPa·m$^{1/2}$. The weld seam was a single V-groove 10 mm wide produced by a shield metal arc weld (SMAW) process and was not subjected to a post-weld heat treatment. The through-thickness residual stress profile is expressed by Eqn. (3) with coefficients of σ_0 = 231.16 MPa, σ_1 = –613.8 MPa, σ_2 = –2756.2 MPa, σ_3 = 8356.2 MPa, and σ_4 = –5006.3 MPa. The vessel's nominal inside diameter and thickness were 490 mm and 10 mm, respectively. The vessel was subjected to an internal pressure of 6.5 MPa, a nominal bending moment of 55 kN-m, and a temperature of 20 ºC. A 15 mm long, 4 mm deep crack was detected by ultrasonic and magnetic particle techniques, respectively. The nearest major discontinuity was 1,000 mm from the crack. The cyclic load applied to the vessel fluctuated between zero and the maximum operating load. The FCGR is given by da/dN = 3.8×10^{-8}ΔK^3, where da/dN is the fatigue crack growth rate (in mm/cycle), and ΔK is the stress intensity factor range (in MPa·m$^{1/2}$).

A level 1 assessment was not applicable in this case since the supplemental load (i.e. bending moment) exists. For the level 2 and 3 option B assessment, the important parameters calculated by the software are shown in column 3 of Tab. 3. The cylinder was predicted to be safe.

For the remaining life analysis, the results from the software and from the MathCAD worksheet are summarized in Tab. 4. The remaining life predicted by the software was 58,246 cycles, which were the summation of a surface crack growth period of 43,848 cycles, and a through-wall crack growth period of 14,398 cycles. The surface crack was recategorized as a through-wall crack with a length and depth of 23.285 mm and 7.949 mm, respectively. The critical crack length was 71.672 mm. By comparing these results with those obtained by MathCAD as listed in column 4 of Tab. 4, it can be concluded that the present FFS software was accurate.

Parameters			Results by present software	
			Example 1	Example 2
Fracture toughness, K_{mat} (MPa·m$^{1/2}$)			63.90	100
SIF (MPa·m$^{1/2}$)	Primary load, $K_{I,p}$	Surface point	2.22	9.87
		Deepest point	6.37	11.40
	Secondary Stress, $K_{I,sr}$	Surface point	17.37	16.20
		Deepest point	20.45	3.97
Reference stress based on primary stress, $\sigma_{ref,p}$ (MPa)			43.94	103.90
Toughness ratio, K_r		Surface point	0.33	0.28
		Deepest point	0.44	0.16
Load ratio based on primary stress, $L_{r,p}$			0.17	0.43
Maximum permitted value of load ratio, $L_{r,p(max)}$			1.43	1.36
Maximum permitted value of toughness ratio, K_{rc}		Level 2	0.996	0.971
		Level 3 option B	0.993	0.947
Integrity status		Level 2	Safe	Safe
		Level 3 option B	Safe	Safe

Table 3: Integrity assessment results of the example problems.

Result		Analysis tools	
		Present software	MathCAD
Remaining life (cycles)	Surface crack growth period	43,848	43,841
	Through-wall crack growth period	14,398	14,402
	Total	58,246	58,243
Crack size just before recategorization (mm)	Length	23.285	23.266
	Depth	7.949	7.944
Crack length just after recategorized (mm)		27.388	27.378
Critical crack length (mm)		71.672	71.644

Table 4: Remaining life analysis results of the CSCCE cracked cylinder in example 2.

CONCLUSIONS

The object-oriented software for fitness-for-service assessment of a cracked cylinder based on the current edition of the API 579 standard has been developed. The software development process was described and a unique class diagram was developed. Extension of the class diagram to include another type of cracked component (e.g. a cracked plate) was conceptually demonstrated. Programming issues were discussed, for example the preparation of information in the standard for coding, handling of a changing of a local coordinate in SIF calculation, crack size updating in fatigue crack growth analysis, and incorporating the effect of residual stress on the fatigue crack growth rate. The software's source code was written in the Delphi programming language. The software is able to perform brittle fracture assessment at levels 1, 2 and 3 option B, leak-before-break assessment, and remaining life assessment of a cracked cylinder subjected to axial force, bending moment, and internal pressure, in addition to stress profiles perpendicular to the crack plane due to mechanical, thermal and residual stresses. The cracked cylinders included in the software had either a through-thickness crack or a semi-elliptical surface crack oriented in axial or circumferential directions. The software incorporated a material database and methods to estimate the fracture toughness and material parameters in the R-O model when the user does not have this data. The software was found to accurately and rapidly perform the assessments.

ACKNOWLEDGMENTS

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