Abstract

The process used to calculate and reduce the consequences of meteoroid and orbital debris (MOD) penetrations and their link to catastrophic failure has evolved over time. As the threat of the orbital debris population increased in the 1980s and early 1990s, NASA developed a tool to determine the probability of no catastrophic failure, or PNCF, for the space station and to assess possible changes in station design and/or operations to improve that survivability percentage. PNCF is directly related to the PNP, or probability of no penetration, as calculated by Bumper, the code used by NASA to perform MOD risk assessments. Part of the process in determining PNCF involves calculating the size of the holes and cracks caused by any penetrations. In this paper, the features of new generic hole- and crack-size prediction equations, as well as the phenomenology involved in the formation of holes and cracks in habitable space station modules are presented and discussed. When these new hole and crack size equations are used in survivability assessments, the fidelity of the PNCF calculations and predictions are expected to increase dramatically.

Keywords: orbital debris, penetration, hypervelocity impact, hole size, crack length, space station, risk assessment

1. Introduction

The approach used to compute and reduce the consequences of a meteoroid (and later, an orbital debris particle) penetration and its link to catastrophic failure (defined here as a crew fatality) has changed over time. The advent of large space structures such as the International Space Station (ISS) has allowed scenarios where many meteoroid and orbital debris (MOD) penetrations could be survivable. As the orbital debris population and the associated penetration threat increased in the 1980s and early 1990s, NASA engineers began to develop a tool that would allow them to determine what percentage of ISS penetrations might be survivable for the crew and the ISS, and to assess possible changes in station design and/or operations to improve that percentage.

Given these developments, NASA developed the MSCSurv computer code for quantifying a so-called ‘R factor’ - the ratio (R) of orbital debris penetrations that would cause either one or more crew losses, or the long term (potentially irrevocable) loss of spacecraft habitability, to all orbital debris penetrations [1]. The overall probability of no catastrophic failure, or PNCF, is computed using the equation:

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where PNP, the probability of no penetration, is given by

\[
PNP = \exp(-N)
\]  

and N is the total number of impacts causing penetration summed over the entire spacecraft surface. PNP is determined using the computer code Bumper, and is a function of particle flux, module surface area, exposure time, and shield ballistic limit [2]. NASA has recently expended significant effort [3] to review Bumper and benchmark it to other MOD risk assessment codes used by some ISS international partners. The R factor is also a function of the parameters noted above, plus HVI damage level, crew operating parameters, and ISS equipment characteristics. By altering the input parameters regarding crew operations, internal arrangement of the ISS modules, and other design factors, an analyst can compare the safety of various existing or proposed modes of ISS operation. A key component of the process MSCSurv follows to calculate R requires use of damage prediction equations to calculate hole size and crack length following an on-orbit module wall penetration by an orbital debris particle [4]. Considering the significance of these calculations, it is imperative that the equations used are as accurate as possible — it is this aspect of MSCSurv that we focus on in this paper.

2. Prior hole and crack size prediction equations

Once a module penetration has occurred, MSCSurv must determine the extent of the damage to the module’s rear, or ‘pressure’, wall. This is defined in terms of the size of the hole created by the impact of the debris cloud formed by the initial penetration of the particle on the outer bumper plate(s) and the length of the associated crack. Predicted hole sizes are defined in terms of the equivalent diameter of a circular hole (so that they can be used in depressurization equations), and crack sizes in terms of maximum tip-to-tip crack length (so that they can be used in determining whether a module ruptures, or “unzips”, causing a catastrophic breach). All models referred to hereafter assume a spherical aluminum orbital debris particle of diameter \( D_p \).

As noted previously in Reference [5], prior to Version 9.0, pressure wall hole size was predicted by MSCSurv using one of two hole-sizing options (selected by the user): the Schonberg-Williamsen (S-W) hole-sizing method [6,7] or the Burch D90 hole-sizing method [8]. The Burch D90 model describes a diameter enclosing 90 percent of the damage on a given plate, and is based on a limited subset of primarily normal impact tests at velocities below 6 km/s. Previous studies (see, e.g., [5]) have shown that not only can the Burch model over-predict hole size compared to the S-W model, but the Burch model (unlike the S-W model) was not developed to have the appropriate behavior near the ballistic limit of the multi-wall system (i.e., hole diameters and crack lengths predicted by the Burch model do not approach zero when the projectile diameter approaches the ballistic limit diameter value from above).

In past MSCSurv assessments, the S-W model, consisting of 13 separate prediction equations for 13 shield types, was generally preferred, if applicable, since it was based on actual test data collected for representative ISS materials and wall configurations, ranging in impact conditions from 0 to 60 degrees obliquity, and at an impact velocity of 6.5 km/s. The effects of impact velocity are incorporated into the hole diameter and crack length predictions by using a momentum scaling factor for hole diameter and an energy scaling factor for crack length. If the S-W model was not applicable for a particular wall system, the more generic, but potentially less accurate, Burch D90 model was used by MSCSurv as an approximation for predicted hole size. Crack length prediction equations used within MSCSurv in prior assessments roughly paralleled the hole size prediction equations in structure and applicability. The S-W crack length equation was derived for the same shields as the S-W hole size equation, but had limited applicability to other shields. In those cases, the Burch D90 hole size equation multiplied by a factor of 2 was used to calculate maximum tip-to-tip crack length.

In earlier MSCSurv risk assessments of the ISS assembly complete configuration, it was typical to find that the Burch model was applied to approximately 85 percent of all orbital debris penetrations, while the more accurate S-W hole size equations were applied to only 15 percent of all orbital debris penetrations [5]. Considering the potentially significant differences between the predictions of the Burch model and empirically-based equations (as well as the lack of physical reality of the Burch model predictions near the ballistic limits of shielding systems), such prominent use of the Burch model in MSCSurv risk assessments was a serious concern that needed to be
addressed. This paper presents an overview of the development of revised hole-size and crack-length models that would address this concern.

In this paper, we first review the features of new generic hole- and crack-size prediction equations, dubbed the Williamsen-Schonberg, or W-S, model, as initially presented in Reference [5] for projectile diameters just beyond ballistic limit values, and then complete the development of the full W-S model by extending it to projectile diameters significantly larger than the ballistic limit values as well as to oblique impacts and impacts involving very thin bumpers. Now implemented in MSCSurv, use of the full W-S model should increase the overall accuracy of MSCSurv risk predictions.

3. The form of the new generic hole and crack size prediction equations

A generic hole diameter-vs-projectile diameter curve is shown in Fig. 1 for a given impact velocity and shield system. The general type of phenomenology shown in Fig. 1 is broken up into 3 regions; each region corresponds to a certain type of projectile response and pressure wall hole growth pattern. The first region is shaded to indicate where hole diameter modeling is currently available. The shape of the curve shown in each of these three regions is based on the following considerations.

Initially, the hole diameter (and the cracking) phenomena are governed by the nature of the debris cloud loading on the module pressure wall. This case corresponds to Region I of the curve shown in Fig. 1. In Region I, the projectile is completely shattered upon impact and the degree of fragmentation increases with increasing projectile diameter. As a result, spread of the debris cloud created by the initial impact also increases as does the effective diameter of the hole in the pressure wall.

However, at a certain projectile diameter (labeled D_1 in Fig. 1), the projectile is too large for it to be completely shattered by the outer bumper or shielding system. Hence, for projectile diameters beyond this point (i.e. in Region II), the amount of projectile fragmentation decreases with increasing projectile diameter as does the spread of the debris cloud and the size of the hole in the pressure wall.

From Fig. 1 it is apparent that the form of the equation for Region I must be such that a maximum (or at least an asymptote) is reached at some point as the projectile diameter increases beyond the ballistic limit value; the hole diameter (and crack length) equations in [6,7] satisfy this requirement. Naturally, the nature and extent of the various regions in Fig. 1 (i.e. large, small, or non-existent) depend on the geometric and material properties of the particular dual- or multi-wall system under consideration.

Fig. 1. Generic Pressure Wall Hole Diameter as a Function of Projectile Diameter [5]
In recognition of the phenomenology discussed above, the new W-S model consists of a single hole size and single crack size equation that may be applied to all of the ISS wall configurations tested previously, as well as other configurations within a similar range of shield design parameters (such as wall thicknesses, bumper areal densities and stand-off distances). Each hole and crack size equation consists of three parts: (1) a data-based equation for Region I of Fig. 1, (2) an interpolation equation for Region II between the data-based equation for Region I and the single-wall equation for Region III, and (3) a single-wall equation for Region III that begins at that projectile diameter where the bumper ceases to be effective in fragmenting an impacting projectile.

Figure 2 below presents a sketch of this three-part equation (thick solid line) that is intended to model the response as outlined previously (still shown as the thinner line with dashes and dots). This figure also includes some generic empirical data to support the premise that the first part of each three-part equation is empirically-based. The thinner dashed lines are shown only to indicate extensions or precursors of the data-based and single-wall equations, respectively, and are not actually used by the model in the regions where they are drawn.

**Region I**

As discussed in [5], the following considerations, based on analysis of several hundred perforated rear walls from dual- and multi-wall target systems impacted by high speed projectiles, were used in determining the form of the equation for this region.

- **Effect of bumper-to-rear wall stand-off**: The larger the stand-off distance between the outer bumper and the rear wall, the lower the likelihood of a penetration, but in the event of a penetration, the bigger the hole or crack.

- **Effect of rear wall thickness**: Rear wall thickness affects the rate of growth of the hole as well as its final size – the thicker the rear wall, the smaller the hole. A thin rear wall also results in a big hole rather quickly. Rear walls of multi-wall systems with strong or massive intermediate bumpers fail after bulging, not by piercing or by through-holes. As a result, in such systems, a big hole happens fairly quickly once the ballistic limit is exceeded.

- **Effect of bumper thickness and intermediate bumpers**: As the ratio of projectile diameter to bumper thickness increases, the debris cloud becomes increasingly concentrated. The more massive an intermediate shield, the larger the hole or crack and the further away from the rear wall it is located, the less of an effect it has (i.e. a light, thin intermediate bumper far away from the rear wall has little or no effect, while a more massive intermediate bumper closer to the rear wall would have more of an effect, producing larger holes in the rear wall). A more massive intermediate bumper decreases obliquity effects (see next) because as debris clouds move through intermediate bumpers, their trajectories become more and more normal which allows them to act more ‘in concert’ again.
Effect of trajectory obliquity: Oblique impacts without intermediate bumpers tend to drive down hole size and crack length. This effect is amplified in walls with large stand-off distances: the larger stand-off distance allows the in-line and normal debris clouds that were created by the initial impact on the bumper to separate, which in turn causes the more damaging particles in the debris clouds to act more independently (i.e. without the damage enhancement of the fuller impulse that would exist if the two clouds acted together), resulting in smaller holes.

Effect of impact velocity: The obliquity effect is more pronounced at lower impact velocities; as velocity increases, there is less and less of an obliquity effect. At higher velocities, rear wall failure is from bulging, and not from piercing or by through-holes. Again, bulging failures make bigger holes more quickly.

It is interesting to note that some of the shield parameters that act to cause larger holes following penetration, such as higher standoff and thicker intermediate shields, can also act to decrease the likelihood of holes (that is, to raise the ballistic limit). In raising the ballistic limit (i.e. the threshold energy limit to produce holes), each of these shield parameters acts like a large energy "dam" – and when it breaks, hole sizes grow rapidly. On the other hand, another parameter that acts to raise the ballistic limit when it is increased – rear wall thickness – also acts to hinder hole growth even after the wall is breached. Ideally, these parameters and their effects on penetration resistance and response must be balanced in shield design to optimize overall spacecraft and crew survivability, that is, to raise the ballistic limit while simultaneously lowering the severity of holes once a shield is penetrated.

Based on these considerations, the following equation forms were used to model hole diameter and crack length in Region I as indicated previously in Fig. 1.

**Hole diameter in Region I:**

\[ D_h = A_h \left( \frac{V_p}{6.5} \right) \cos \theta_p \left( 1 - \text{exp} \left[ -C_h \left( \frac{D_p}{D_{BL}} - 1 \right) \right] \right) \]  

Expressions for \( A_h, B_h, \) and \( C_h \) can be found in Reference [5], and were obtained by first determining an appropriate baseline set of values for these parameters for the U.S. Lab Cylinder module wall system for 6.5 km/s impacts, and then adjusting these baseline values to fit the test data for the other wall systems according to the phenomenological considerations outlined above.

**Crack length in Region I:**

\[ L_n = A_L \left( \frac{V_p}{6.5} \right) \cos \theta_p \left( 1 - \text{exp} \left[ -C_L \left( \frac{D_p}{D_{BL}} - 1 \right) \right] \right) \]  

where the parameters \( A_L, B_L, \) and \( C_L \) were obtained using the same process as before and are also given in Reference [5].

This completes the development of the W-S model as presented in Reference [5]. This model is now extended to the case of very thin bumpers (i.e. less than 25% of the equivalent thickness or areal density of the rear pressure wall). In such cases, an adjustment to the values calculated by Eqs. (3,4) to account for the decreased ability of the (very) thin bumper to break up the impacting projectile. This adjustment is made using the following linear interpolation between the value calculated by, for example, Eq. (6), and the value calculated using a single wall hole size equation as applied to the entire dual- or multi-wall system (see Region III):

\[ D_h' = D_h^{\text{rel}} + \left( \frac{t_b}{t_w} \right) / 0.25 \left( D_h - D_h^{\text{rel}} \right) \]  

where \( D_h \) is calculated using Eq. (3) and \( D_h^{\text{rel}} \) is calculated using the process described in Region III for the projectile diameters in Region I, and the quantities \( t_b \) and \( t_w \) (bumper thickness and rear wall thickness, respectively) are equivalenced to the same material. Finally, we also note that in Eqs. (3-5), \( V_p \) (in km/s), \( \theta_p \), and \( D_p \) are the impact velocity, trajectory obliquity, and diameter of the impacting projectile, and \( D_{BL} \) is the ballistic limit diameter (in consistent units) for the shield of interest at impact velocity \( V_p \) and trajectory obliquity \( \theta_p \).

**Region II**

In this region, the hole diameter and crack length equations for Region I are extended to larger projectile diameters to account for the decreasing effectiveness of bumpers in breaking up the debris cloud. The hole size
values between $D_p=D_1$ (i.e. the Region I / Region II interface) and $D_p=D_2$ (i.e. the Region II / Region III interface) are obtained by interpolating between the values predicted by empirical equation developed for Region I (and extended into Region II) and the values obtained using a single wall hole size prediction equation (as described in the following section). The values of $D_1$ and $D_2$ are likely to be dependent on the material properties and geometric parameters of the shield design, as well as on impact velocity and trajectory obliquity. The following methods were used to determine preliminary estimates for these values.

First, the boundary between Region I and Region II is presumed to occur when the projectile is too large for it to be completely shattered by the outer bumper or shield. Hence, beyond $D_p=D_1$ the amount of projectile fragmentation decreases with increasing projectile diameter. A review of the literature on the effectiveness of thin plates to fragment projectiles revealed that aluminum bumper plates begin to be effective in protecting a rear wall against perforation by aluminum projectiles as the $t_b/D_p$ ratio is increased above ~0.05 (with an optimal $t_b/D_p$ ratio of ~0.25). Therefore, for the purposes of this study, it is assumed that the Region I / II boundary occurs at $D_p/t_b = \sim 20$.

Second, beyond $D_p=D_2$ the projectile is so large relative to the thickness of the bumper that the bumper has hardly any effect on the impact projectile. In such a case, the diameter of the hole in the bumper plate is likely to be just a fraction larger than the diameter of the projectile itself. For example, if we assume that the ineffectiveness of the bumper is said to occur when the hole in the bumper plate is only 10% larger than the diameter of the projectile, then invoking the following equation from Reference [9] for the size of a hole in a thin plate we have:

$$1.1D_p = 0.45D_p [V_p (t_b / D_2)^{2/3} + 2]$$  \hspace{1cm} (6)

Solving for $D_2$ yields:

$$D_2 / t_b = (V_p / 0.444)^{3/2}$$  \hspace{1cm} (7)

Therefore, for an impact velocity of 6.5 km/s, $D_2/t_b = \sim 55$. Thus, for a given value of $t_b$, the corresponding value of $D_2$ can be readily calculated. Further study could undoubtedly lead to improvements of the assumed values of $D_1/t_b$ and $D_2/t_b$.

It is also important to note that in the event that the outer bumper is exceedingly thin (i.e. less than 25% of the thickness of the rear pressure wall), then the interpolation in Region II is between the values predicted by the thin bumper interpolation equation developed for Region I and extended into Region II through the continued use of Eq. (5) and the values obtained using the Region III single wall hole size prediction equation in Region II.

**Region III**

In this region, the hole diameter and crack length equations for Region II are extended to larger projectile diameters. The hole prediction equation is extended using the method proposed in the Russian Space Agency’s probabilistic risk assessment [10]. In this approach, it is presumed that the particle size is so large that the bumper thickness is inadequate to fragment the particle upon impact. In this case, bumper perforation occurs without significant particle fragmentation or erosion, and the particle impacts the rear wall pretty much intact. Under such conditions cracks would not be expected to emanate from the hole in the rear wall caused by the large impacting particle; in effect, the “maximum tip-to-tip crack length” in such a case could be construed to be simply the diameter of the hole created in the rear wall. With this assumption, we then return our attention to developing the equation for rear wall hole diameter in this region.

Under the assumptions and conditions noted above, the size of the hole in the rear wall of the dual-wall system in this impact regime can be calculated using any number of equations that predict the size of a hole in a single thin plate following a perforating hypervelocity impact. The diameter of the particle impacting the rear wall would be taken to be the same as the diameter of the original projectile and its impact velocity would be slightly reduced from the original impact velocity because of momentum conservation.

Specifically, if we restrict our discussions (for now) to normal impacts, the following equation can be used to predict the hole diameter both in the initial impact on the bumper and for the subsequent impact on the inner or rear wall of the dual-wall system [11]:

$$D_h = 0.45D_p \left[ V_p \left( t_b / D_p \right)^{2/3} + 2 \right]$$  \hspace{1cm} (8)
where the parameters are defined depending on whether Eq. (8) is used on the bumper plate or on the rear wall plate. The procedure to calculate the diameter of the hole in the rear wall in Region III is then as follows:

1. Use Eq. (8) to calculate the size of the hole in the bumper to determine the mass of the bumper material ejected by the initial impact. In this case, \( D_h \) is the hole diameter in the bumper, \( D_p \) is the diameter of the impacting particle, \( t_b \) is the bumper thickness, and \( D_p \) is the impact velocity (in km/s).

2. Impose momentum conservation to calculate the velocity of the particle after the initial bumper perforation. This is accomplished as follows:

\[
m_p V_{pf} = m_b V_p + (\pi/4)D_h^2 t_b \rho_b V_p \quad \text{→} \quad V_{pf} = V_p / \left(1 + \pi D_h^2 t_b \rho_b / 4m_p \right) \quad (9a,b)
\]

where \( m_b \) is the mass of the impacting particle, \( D_h, t_b, \) and \( V_p \) are as defined above, \( V_{pf} \) is the particle velocity after it exits the bumper plate (i.e., it is the impact velocity for the rear wall hole diameter calculation), and \( \rho_b \) is the density of the bumper material (in appropriate units).

3. Use Eq. (8) to calculate hole diameter in the rear wall using \( V_{pf} \) instead of \( V_p \) and \( t_w \) (rear wall thickness) instead of \( t_b \). In this re-application of Eq. (8), we assume that the projectile mass (or rather, its diameter) effectively remains unchanged.

This completes the development of the rear wall hole diameter equation for Region III.

4. Results and Discussion

Region I

Figures 3 and 4 below present comparisons of hole size and crack length predictions as given by the previous S-W model and the new W-S model presented herein. Also presented in these figures are the data used to derive the empirical S-W model equations so that we can also see how well the new W-S model equations compare against it. The results shown in these figures are representative of those seen in the full suite of comparative plots, which can be found in Reference [12].

In these figures, we see that the S-W model either did not fit the data well (e.g., Fig. 4), or in those cases where it did, its plot was irregular in that it did not show the expected asymptote as projectile diameter increased beyond the ballistic limit (e.g., Fig. 3). In these cases, the new W-S model either fit the data just as well or better, but also displayed the proper asymptotic behavior. Taking these results and others like it under consideration, we believe that the W-S hole and crack size model is an improvement over the S-W model used by MSCSurv Version 7.0.

Regions II and III

Figure 5 shows a plot of the complete W-S rear wall hole diameter prediction for the US Lab Cylinder wall system for a 6.5 km/s impact at a 0-deg trajectory obliquity (for this wall system, \( t_b/t_w \approx 0.265 \)). This figure also shows the S-W hole diameter model (solid blue line) for comparison purposes. As can be seen from this plot, the three parts of the W-S model (solid purple, solid green, and solid red lines) fit together nicely, with Regions I and II intersecting at the assumed projectile diameter-to-rear wall thickness (\( D_p/t_b \)) ratio of 20, and with Regions II and III intersecting at the prescribed value of 55. Furthermore, the interpolation equation for Region II is seen to decrease initially just beyond \( D_p/t_b = 20 \), then rise up to meet the single hole equation at \( D_p/t_b = 55 \). Thus, the Region II portion of the model captures the essence of the hole size phenomenology as discussed previously. The dashed lines seen in Fig. 5 only serve to indicate extensions or precursors of the various parts of the W-S model, and are not actually parts of that model in the regions where they appear.

Figure 6 shows a generic plot for the case of a very thin bumper, specifically, the case where \( t_b/t_w = 0.125 \). The three parts of the W-S model (solid purple, solid green, and solid red lines) are again seen to fit together very nicely, with the interpolation in Region II connecting to the thin bumper interpolation at the Region I / Region II boundary, as well as with the single wall hole equation at the Region II / Region III boundary. As before, the dashed lines are shown only to indicate extensions or precursors of the various parts of the W-S model, and are not actually parts of that model in the regions where they appear.
5. Oblique impacts in Regions II and III

The process described above can be easily adapted to the case of non-normal or oblique impacts in Regions II and III. The W-S model for Region I already includes obliquity effects, so all that remains is to introduce obliquity effects in Region III — obliquity effects will then be automatically included in Region II since the W-S model in Region II is an interpolation between Region I and Region III. To introduce obliquity effects in Region III, all that is needed are equations that predict the maximum and minimum dimensions of the hole created by the oblique impact of a hypervelocity projectile on a thin plate. Such equations can be found in a number of references, including Ref. [13]. Once these dimensions have been found, the process continues as follows.

(1) Calculate an equivalent circular $D_h$ for the bumper plate hole by equating the area of the actual elliptical hole created by the oblique impact to a circular hole with diameter $D_h$.

(2) Use this value of $D_h$ in Eqs. (9a,b) to calculate $V_{pf}$ as before.
(3) Considering the size of the projectile relative to the geometric parameters of the impact system, it would appear to be reasonable (and consistent) to assume that the path of the projectile is unaffected by its penetration of the bumper plate (or at least nearly so). In this case, now use the same oblique impact hole dimension prediction equations to calculate the hole diameter in the rear wall using $V_{pf}$ instead of $V_p$ and $t_n$ instead of $t_b$.

(4) Calculate an equivalent circular $D_h$ for the rear wall hole by equating the area of the actual elliptical hole to a circular hole with diameter $D_h$.

This completes the development of the rear wall hole diameter equation for Region III for the case of oblique impacts, and also provides the $D_h$ values necessary for the interpolation calculations performed to develop rear wall
hole values for Region II (in the case of very thin bumpers, this value of $D_h$ is used as $D_h^{sw}$ in the Region II interpolation process).

A final consideration is the location of the Region II / Region III boundary (the boundary between Region I and Region II is presumed to remain as previously indicated). The $D_2/t_b$ value defining the Region II / Region III boundary for oblique impacts can be found using the same process as outlined previously for normal impacts, except that the algebra might be a bit more cumbersome. Additionally, we recommend that the maximum crack length prediction in Region III be formulated using the maximum dimension of the elliptical hole generated in Step (4) above. The values for crack lengths in Region II would be interpolated in a similar fashion between the crack lengths predicted for Region I and the maximum elliptical hole dimension calculated for Region III.

6. Concluding comments

NASA currently uses the MSCSurv code together with Bumper to calculate the probability of no catastrophic failure, or PNCF, of the ISS due to MOD particle impact. As part of this calculation, MSCSurv must consider numerous assumptions regarding crew and ISS response to an impact. One of the most important of these considerations is the calculation of a hole size and a crack length following an on-orbit penetration for each of the many different ISS shield types. In this paper we have presented a new model for calculating these quantities. Based on the results obtained thus far, we believe that the new hole and crack size model encoded will improve the fidelity of the PNCF predictions by MSCSurv. Of course, this remains to be confirmed by comparing the PNCF predictions of MSCSurv before and after the implementation of these new hole and crack size models in MSCSurv.

Acknowledgements

The authors would like to acknowledge the support provided by the NASA Engineering and Safety Center and the NASA Johnson Space Center that made this work possible.

References