# NUMERICAL EVALUATION OF COLDWORKED RIVETED JOINTS

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***Abstract.*** *The process of coldwork is usually applied to riveted joints, aiming to increase their resistance against fatigue. This process is very often used in critical structures of new and aging aircraft. In the present work, two different approaches for modeling and quantifying the coldwork process are studied. The first approach is a more conventional one, in which the hole is expanded from its initial diameter, and then submitted to a machining process in order to achieve its final dimension and the desired surface finishing. Hence, part of the compressive zone generated after the cold expansion is removed. The second approach has the advantage of preserving the resulting compressive zone, since the initial diameter is sized as a function of the desired hole size, and therefore the machining process is no longer necessary. In both cases, residual compressive stresses are generated around the hole, which are beneficial in terms of fatigue resistance, since crack initiation and propagation can be considerably delayed. This article presents a quantitative analysis of the coldwork process. The compressive zone around the hole is modeled via finite element analysis using MSC.Nastran. Then, the crack propagation analysis is performed using Nasgro software. New Nasgro solutions use "weight functions" in order to evaluate stress intensity factors for non-linear stresses symmetrically distributed around cracked holes. Finally, the benefits of the coldwork process on predicted fatigue lives of a typical riveted joint are numerically evaluated.*

***Keywords****: crack propagation, riveted joints, coldwork, weight function, and damage tolerant.*

## 1. Introduction

Fatigue in aeronautical structures has become an important subject since the Second World War. Firstly, many important military resources were lost, due to repeating catastrophic failure of military airplanes, requiring deep investigation on fatigue. Secondly, the civil aviation debuts the "jet age" with "De Havilland Comet", when the general public discovered the amazing qualities of a new transportation system, but a series of catastrophic failures followed this innovative airplane. The investigation resulted in new laboratory test methods, and the development of new failure theories.

Nowadays, the certification process requires a series of laboratory tests, and it also imposes requirements to the development of new aircraft. Those requirements suggest the type of failure criteria to be considered, depending on the kind of structure taken into account, and the level of critical loads applied. There are three failure criteria adopted by the industry: safe life, fail safe and damage tolerant.

Safe life uses S-N curves to estimate the number of cycles a component can withstand until failure. Huge factors of safety are considered, which implies in premature retirement of airplanes. Fail safe is an approach that requires the duplication of a component, or at least the existence of redundant load paths and deviated from a component in case of its failure.

Damage tolerant failure criteria consider the number of cycles (flights) between the initial crack size (detectable) and the critical crack size (failure). This is an efficient and economical approach, which permits the definition of inspection intervals (considering a safety margin). The smaller the detectable crack size, the more rigorous (and costly) is the inspection method, and larger the inspection interval.

This article considers the Linear-Elastic Fracture Mechanics theory to calculate crack propagation in riveted joints. The damage tolerant failure criterion is particularly important in this context, because crack initiation is delayed in a cold expanded joint.

The benefits of the coldwork process to reduce crack propagation were numerically evaluated in a hypothetical joint subjected to high stress levels. Two variants of the coldwork process are considered: split-sleeve; and cold expansion to size (FTI, 2004).

The coldwork process has been employed largely in both civil and military aircraft. The objective is to increase the fatigue life of critical components under high stress levels. This process is applied in new airplanes projects, as well as in aging airplanes, in which the operational service is expanded (Swift, 2000).

## 2. Methodology

The stress distribution around holes resulting from a remotely applied load can be predicted from the theory of elasticity (Timoshenko and Gere, 1970). Equation (1) is used to calculate the stress distribution around the hole.

$$\sigma_\theta = \frac{S}{2}\left(2 + \frac{a^2}{r^2} + 3\frac{a^4}{r^4}\right) \tag{1}$$

- S: remote stress.
- $\sigma_\theta$: tangential stress.
- a: hole radius.
- r: distance from the hole center to the plate border.

The finite element method was used to simulate the expansion process. *MSC.Nastran* was used to accomplish this task. An enforced displacement is applied to the hole, which value is calculated using Eq. (2), and represents the expansion level that the hole is subjected. Plastic deformation and the residual stress field are obtained after unloading.

$$Expansion = \frac{\o_f - \o_i}{\o_i} \times 100\% \tag{2}$$

- $\phi_i$: initial diameter.
- $\phi_f$: final diameter prior to unloading.

## 3. Coldwork process description

The process called “Split Sleeve Cold Expansion” (FTI, 2004) is widely used in aeronautical industry. A mandrel with a lubricated split sleeve is inserted in a pre-hole (see Fig. 1). The split sleeve protects the hole against damage, and it ensures that the process is executed in only one direction. The mandrel expands the hole (i.e. enlarges its diameter), and it is pulled backward. Next, the split sleeve is removed, and finally the hole is reamed to final size and surface finish. The machining process removes a considerable part of the residual stress zone.

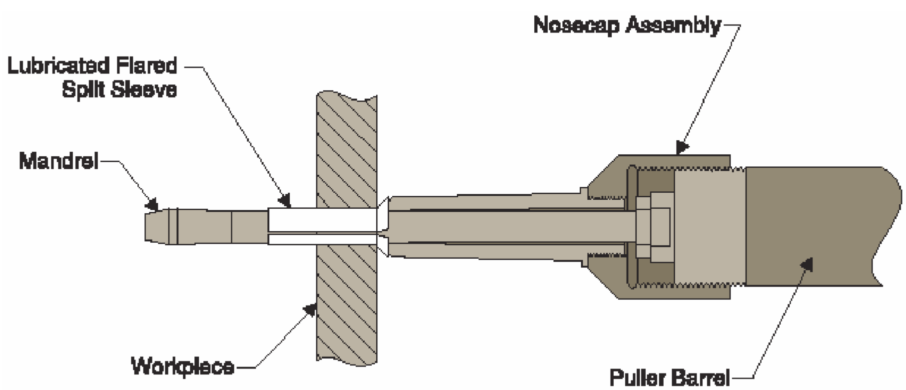



Figure 1. Split Sleeve Cold Expansion (adapted from FTI, 2004).

A variation of the “standard” process is known as “Cold Expansion to Size”. It differs from the standard process because the machining process is not required. This process is planned considering the material properties and the hole final diameter after unloading. Therefore, this process must be more controlled than the standard one, but has the advantage of preserving the compressive residual zone intact.

## 4. Weight Function

Weight function methods are used to calculate the stress intensity factor of irregular stress loading, as it is the case when the remote loading is superimposed with the compressive residual stresses due to coldwork.

Consider a bi-dimensional linear elastic body with a crack under plane strain state (or generalized plane stress state), such as the through crack geometry illustrated in Fig. 2. Both body and loading conditions are symmetrical about the crack tip plane, so that only mode I crack opening takes place (Rice, 1972). If the displacement field and the stress intensity factor are known for that geometry, the weight function (h) can be calculated using:

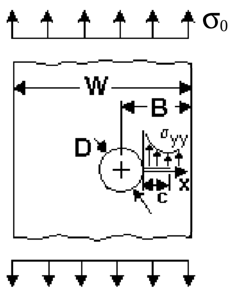
$$h = h(x,c) = \frac{H}{2K_1}.\frac{\partial u}{\partial c}$$
$$H = E\big/(1-\nu^2) \tag{3}$$

- H: elasticity modulus for plane stress state.
- $K_1(c)$: stress intensity factor.
- u (x, *c*): displacement field.

The stress intensity factor for an arbitrary loading condition ($K_2$) can be calculated using:

$$K_2 = \int_\Gamma t.hd\Gamma + \int_A f.hdA \tag{4}$$

- t: traction vector acting around contour Γ.
- f: body force acting on area A.




- W: plate width
- B: distance between the hole center to plate boundary
- D: hole diameter
- c: crack length
- $\sigma_{yy}$: irregular stress distribution
- $\sigma_0$: symmetrical remote loading

Figure 2. Through Crack (adapted from *Nasgro*, 2004)

The stress distribution around the hole is superimposed with the residual stress due to coldwork. Conventional crack propagation methods can not use the resultant stress field as input, but this difficulty is overcome using the weight function method that is already implemented in *Nasgro*'s TC13 solution. Then, the non-linear resultant stress field is used to calculate the crack propagation, which was done using the software *Nasgro*.

Moreira *et al* (2004) discuss the weight function method used to compute stress intensity factors for increasing values of interference due to coldwork.

## 5. Material properties

The aluminum alloy 7050-T7452 was the plate material used. The mechanical properties were obtained from MILHDBK-5H (1998), and are summarized in Tab. 1.

Table 1. Elastic-plastic bi-linear material properties, Al 7050-T7452.

| Young Modulus, E (GPa) | Yield Stress, $\sigma_y$ (MPa) | Poisson's ratio, μ |
|---|---|---|
| 70.3 | 434 | 0.33 |

The stress-strain curve for this material is also available in MILHDBK-5H (1998). The curve format fits the bi-linear elastic-plastic model, which was considered in the finite element analysis. Five points were extracted for non-linear analysis (material non-linearity) using *MSC.Nastran*. The stress-strain points in gray scale summarized in Tab. 2 represents: yield stress and ultimate stress.

Table 2. Stress-strain data for Al 7050-T7452.

| σ (MPa) | ε (%) |
|---|---|
| 0 | 0.0 |
| 434.4 | 0.6 |
| 448.0 | 0.7 |
| 468.5 | 0.8 |
| 475.4 | 0.9 |

The material properties were considered stable during crack propagation analysis, although real materials may behave differently when subjected to cyclic loading. Some will progressively harden, and others will progressively soften. Another transient behavior may occur when the medium stress is different than zero, which is known as cyclic relaxation. Those effects will be considered in future investigation.

**6. Case study**

The model geometry is summarized in Tab. 3. Figure 3 illustrates the top view of this model. The nominal diameter ($ø_n$) represents the model diameter after coldwork machining process, or the final dimension where the rivet is fixed. The initial diameter ($ø_i$) is the pre-hole, where coldwork process takes place. The external diameter ($ø_e$, ten times the nominal diameter) is an arbitrary dimension that must be large enough to represent an infinite plate.

Table 3. Model Geometry.

| $ø_n$ (mm) | $ø_i$ (mm) | $ø_e$ (mm) | t (mm) |
|---|---|---|---|
| 6.35 | 5.72 | 63.5 | 5.5 |

The finite element analysis model has five thousand elements: twenty along the radius, forty along the length, and five along the thickness. It is symmetric about three planes in order to reduce the number of elements. Appropriate convergence tests were carried out to ensure that the number of elements along each dimension is representative, and also to ensure that the plate behaves as an infinite plate. The three dimensional model was used to investigate the stress variation along the thickness, although the method chosen for crack propagation only considers the tangential stress in two dimensional representation.

The cold expansion for this nominal diameter is 4.34%, according to Fatigue Technology (2004) process manual. After spring back, the plastic deformation is 2.67% at the edge of the hole ($ø$ = 6.0 mm). Figure 3 illustrates the compressive tangential stress field ($\sigma_t$), which results from finite element analysis using *MSC.Nastran*. The plastic zone extends for up to three times the diameter of internal hole.

Figure 4 illustrates the tangential stress field at the border and at the center of the plate. The observed difference is due to plane stress state in the border, and general stress state in the center of the plate. The difference between these two stress fields disappears with a radial distance equal to one and a half times the border diameter (Saint Venant effect). High values of compressive stress at the border of the hole occur, and a positive tangential stress field maintains equilibrium.

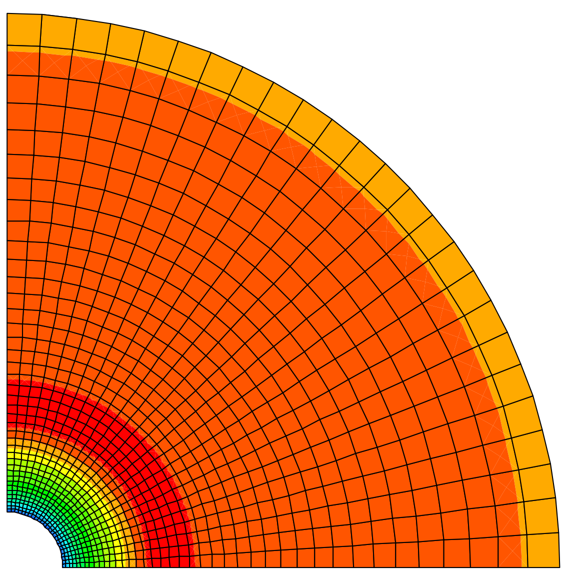


Figure 3. Finite element model illustrative representation results after unloading.
The fringe represents tangential stress variation on top plane.

The fringe color of Fig. 3 corresponds to the tangential stress distribution on top plane illustrated in Fig. 4. The dark blue color represents high compressive stresses, the green to yellow color represents positive stresses, and red color represents high positive stresses.

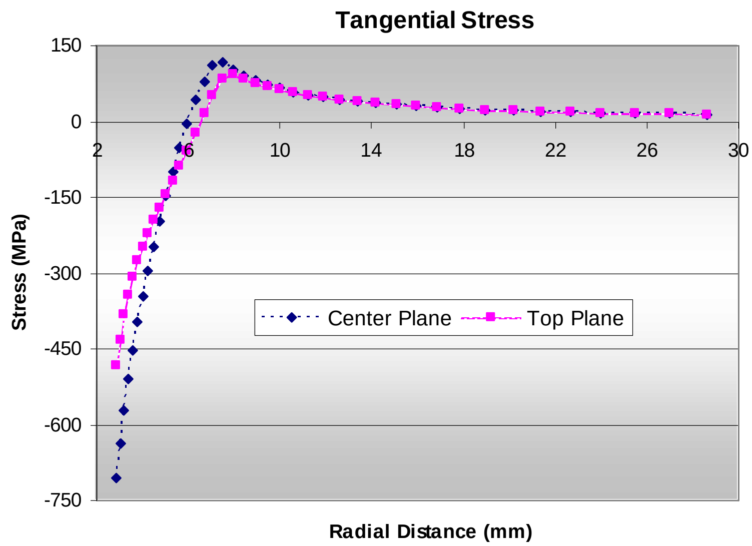



Figure 4. Tangential stress variation: top plane and center plane of the plate.

For conservative purposes, the top plane stress field was used for crack propagation. Equation (1) is used to calculate the stress distribution around the hole due to application of a remote loading. The crack propagation is assumed only occurs if positive stresses exist. Then, the stress distribution due to remote loading must be high enough to overcome the residual stress field.

A series of crack propagation analyses were conducted with superimposed stress distributions. Figure 5 illustrates the residual stress distribution obtained for the case study superimposed with the stress distribution due to remote loading of 140 MPa.

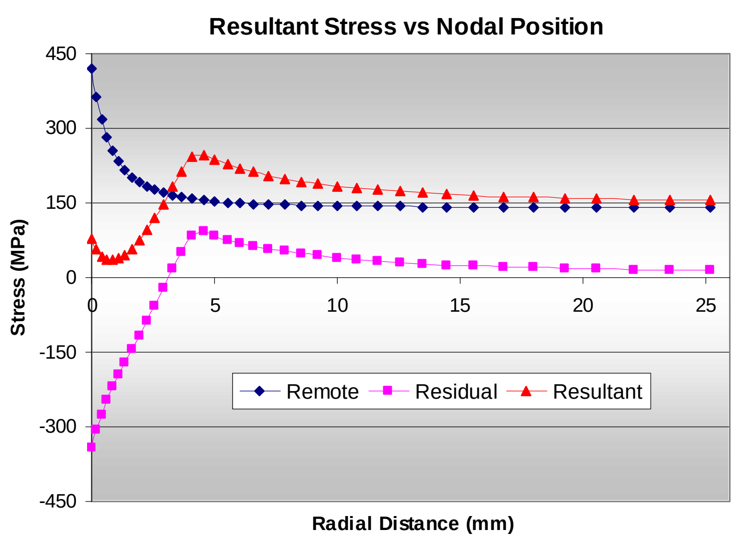



Figure 5. Superimposed (resultant) tangential stress field

Table 4 summarizes the results for crack propagation analysis using *Nasgro*. The number of flights obtained (ground-air-ground cycles) for the riveted joint with coldwork is about 220 times greater than without coldwork.

Table 4. Crack propagation analysis for cyclic stress of 140 MPa.

| Propagation Analysis | Number of Flights |
|---|---|
| Without coldwork | 12,084 |
| With coldwork | 2,660,340 |

Figure 6 illustrates the crack size versus number of flights for the joint without coldwork. Figure 7 illustrates the crack size versus number of flights for the joint with coldwork.

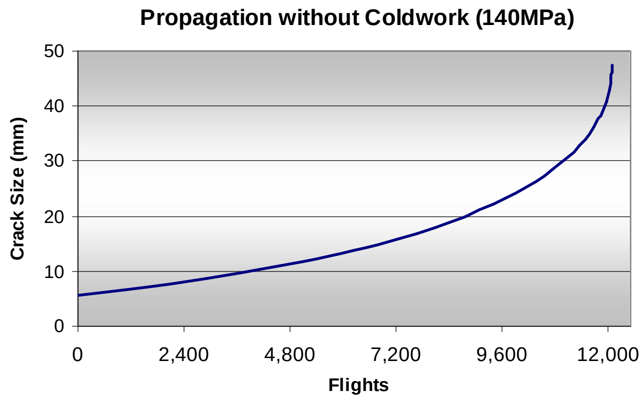



Figure 6. Crack propagation for joint without coldwork for cyclic remote loading of 140 MPa.

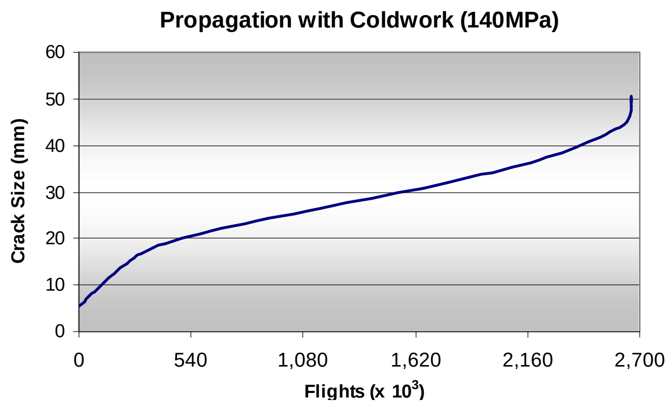



Figure 7. Crack propagation for joint with coldwork for cyclic remote loading of 140 MPa.

Figure 8 illustrates the results of successive crack propagation analysis by increasing the remote loading applied and computing the number of cycles until the critical crack size is reached (failure). The number of flights reduces steadily when the remote cyclic loading increases from 140 MPa to 160 MPa.

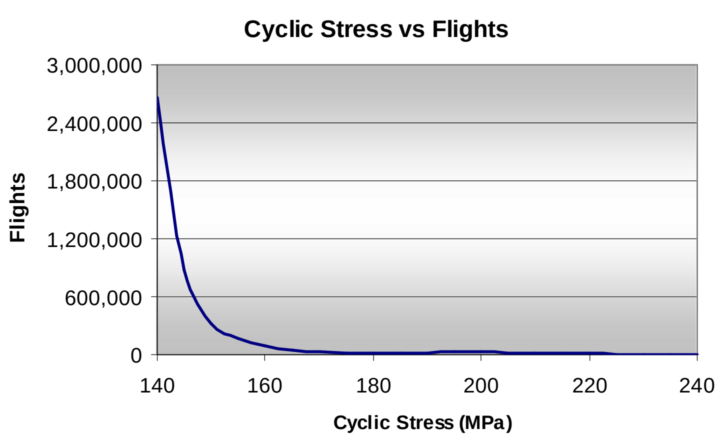



Figure 8. Results of successive crack propagation analysis.

The results obtained encourage the usage of the coldwork process when the part is subjected to high cycle loading. The subjective understanding of the coldwork process may be substituted by the methodology introduced herein.

**7. Case study two**

The case study one is considered the "standard" coldwork process, in which the machining process removes a portion of the compressive residual stress zone. A variation of the standard process, "cold expansion to size", eliminates the machining process that preserves the integrity of the compressive zone.

A similar model of case study one is used in this approach. The only difference is that the pre-hole is a function of the projected level of expansion to be applied and the nominal diameter ($ø_n$). So, the process is geometrical and material dependent.

Residual stress field for different levels of coldwork can be achieved. Notice the increasing plasticity as the expansion grows from 3% to 6% in Fig. 9. The same methodology used to compute the residual stress field, the remote loading stress distribution, and superimposed stress field in case one is used again. The only difference is that the residual compressive zone is fully preserved.

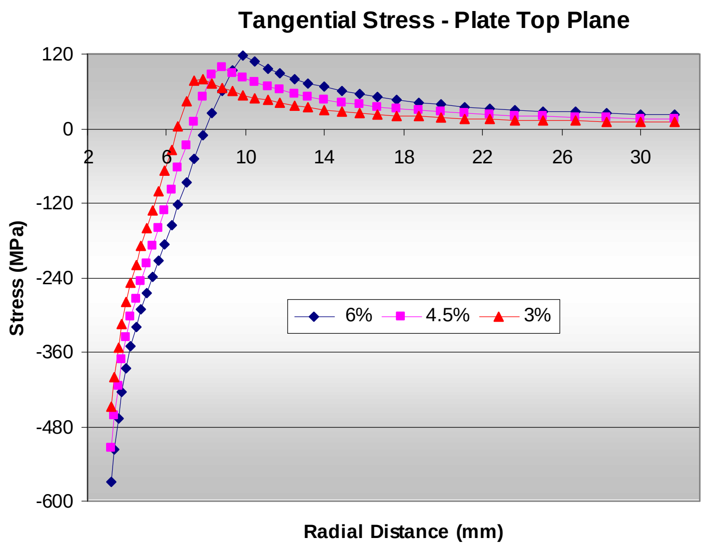



Figure 9.Tangential stress for three levels of coldwork.

The crack propagation results are presented in Tab. 5 for various cyclic loading and expansion levels. Considering a remote loading of 200 MPa, the cold expansion at 3% presents benefits in the order of 21 times over the same model without coldwork. At 4.5%, the expanded model has 764 times more cycles. No propagation occurs at 6%.

Table 5. Crack propagation analysis for different levels of cyclic loading

| Cyclic Stress | Coldwork | | | |
|---|---|---|---|---|
| | 0.0% | 3.0% | 4.5% | 6.0% |
| 175MPa | 5,180 | 3,842,778 | inf. | inf. |
| 200MPa | 3,289 | 72,091 | 2,514,623 | inf. |
| 220MPa | 2,358 | - | 130,666 | 2,434,522 |
| 250MPa | 1,485 | - | - | 54,680 |

**8. Case study comparison**

Table 6 compares case study one (C1) and two (C2) in terms of crack propagation results.

Table 6. Comparison between case study one (C1) and case study two (C2)

| Cyclic Stress | Without coldwork | With coldwork | | |
|---|---|---|---|---|
| | - | C1 - 4.34% | C2 - 3.0% | C2 - 4.5% |
| 140MPa | 12,084 | 2,660,340 | inf. | inf. |
| 175MPa | 6,011 | 22,052 | 3,842,778 | inf. |
| 200MPa | 3,902 | 24,378 | 72,090 | 2,514,622 |
| 220MPa | 2,839 | 9,373 | - | 130,666 |

The advantage of the coldwork process is obvious for both case studies. Considering again a remote loading of 200 MPa, C2 expanded at 3% and 4.5% has 3 and 103 times more cycles than C1 expanded at 4.34% respectively. The machining process introduced in case study one removes a significant portion of the compressive zone (-140 MPa). Then, case study two presents better results in terms of crack propagation even with lower levels of cold expansion.

## 9. Conclusion

The methodology presented in this article is able to numerically evaluate the coldwork process. Non-linear finite element analysis is effective to calculate the residual stresses. Two different coldwork processes were evaluated: “split sleeve cold expansion”, and one of its variations: “cold expansion to size”. The weight function procedure computes the stress intensity factor of irregular stress distribution for crack propagation analysis.

Further study will develop this methodology to take into account real load spectrum. Although simplified, the method can compute crack propagation for simple remote load spectra in cold worked joints, which must be high enough to overcome the residual compressive zone. In practical applications, few load spectra arises above the compressive stress zone. Then, after some adjustments the methodology would be used in practical applications.

Another effect that will be considered in future investigation is the cyclic relaxation of the residual compressive stress zone (introduced by the coldwork process), which may be significantly reduced when cyclic loading is applied.

Some other effects must also be taken into account, such as cyclic loading sequence, plastic deformation around holes in plates due to stress concentration, rivet interference, and stress variation along the thickness. Some of these effects are discussed in the literature (Dowling, 1999). Automation through computer programming is required to enhance the methodology presented herein, so that some of those effects will be considered in calculation.

Laboratory tests are required to confirm the results presented in this article, and it will be valuable to calibrate the methodology with real results.

## 10. Acknowledgements

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## 12. Responsibility notice