A Mixed Lubrication Model for Inter-Ply Friction Behavior of Thermoset Prepregs

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ABSTRACT

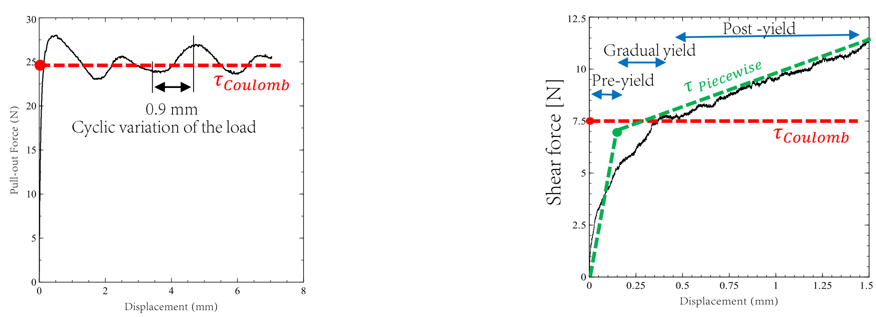
Inter-ply friction plays a dominant role in the generation of fiber-path defects (e.g. wrinkling) in forming and consolidation stages of continuous fiber-reinforced composite laminates. It is generally believed that the constraints imposed by friction between subsequent plies are one of the major factors in the deformations generated during composites forming. The sliding between the plies is mainly influenced by the material parameters such as polymeric matrix and external processing conditions such as forming rate, temperature, and pressure applied. For some thermoset prepregs, the mixed lubrication regime has been found to be the dominating factor over the range of processing window. This article discusses our recent progress towards computational modeling of the inter-ply friction behavior of thermoset prepreg composite systems. To this end, a generic approach is developed to describe the mixed lubrication regime by applying a thin-film theory for hydrodynamic lubrication and load sharing between the fibers. A homogenized resin film thickness is derived from this analysis, rather than postulated as in earlier publications. The computational framework considers the thermal effects and flow compaction in the ply-ply contact area and the influence of the resin rheology, enabling the model to be verified against inter-ply friction experiments under a broad range of processing conditions. The model has been exemplified on an aerospace-grade carbon/epoxy prepreg. Promising agreement was found between the experiments, the mixed lubrication model and earlier empirically determined master curves.

KEYWORDS: *Thermoset composites, Forming, Inter-ply friction, Mixed lubrication*

1 INTRODUCTION

Fiber-reinforced polymers composites are now among the top materials of choice in high-tech sectors including aerospace and automotive due to their superior strength-to-weight ratios, thermal stability, and reasonable manufacturing costs [1]. Lightweight and yet very strong mechanical characteristics of this branch of materials are, however, often disadvantaged by long development time, and potential poor quality due to manufacturing defects, particularly in geometrically complex parts [2]. One of the main difficulties associated with the manufacture of continuous-fiber textile composites is ‘wrinkling’, which is regarded as a critical quality issue by designers, and it can lead to the reduced mechanical properties and lifespan of the final structure by as high as 80%, potentially causing a massive economic loss for companies [3]. The severity of wrinkling can be affected by various manufacturing factors, including mold selection, fiber material characteristics, composite lay-up, the interaction between plies, and quality of processing equipment [4]. In essence, a generation of excess length due to the inability of each composite layer to slip over one another during forming or consolidation can trigger the fibers to buckle out-of-plane and lose the inter-layer cohesion from the adjacent layers. The solution to such manufacturing problem can be achieved thorough an in-depth understanding surrounding the fundamental mechanisms behind the forming of the defect, which is currently incomplete in the literature.

A key process parameter that has been shown [5] to be a mechanism behind the formation of wrinkling defect, is the interaction between plies while curing a composite. The stresses developed by process-induced deformations are partially or fully relaxed by inter-ply friction (also known as inter-ply shear or slippage). Due to the high mobility of the resin, the behavior of thermoset prepregs can be substantially different from their thermoplastic counterparts, and extra measures should be considered as to accurately capture the material behavior for forming and consolidation applications. Initial modeling of this behavior has typically been to represent the yield point with a simple coulomb friction model [6]; however, it is noted that the system is clearly much more complex. Figure 1 shows a typical load trace of an inter-ply shear experiment for a dry fabric and prepreg system. The dry fabric (with no resin) closely follows the classic Columb friction, while the prepreg exhibits a more or less visco-elastic response and results in a significant overestimation of the shear stress before the yield. The complexity of this behavior arises from the consolidation of thermoset fiber reinforced plastics (FRPs) which coupled mechanisms such as the resin rheology and cure behavior. Other mechanisms controlling the compaction phenomena are related to the fiber bed architecture; namely, permeability and elasticity. Examining the composites processing literature, there is a considerable discrepancy in interpreting the frictional response of different materials, particularly at elevated temperatures. For instance, the differences between the magnitude of frictional force at various pressures, rates, and temperatures are still not quite clear and the observed trends are usually fed to empirical models and master curves, in order to be used in finite element simulations [7-11]. More generic predictive finite element (FE) models can play an important role to understand the impact of different process conditions, allowing a wider and more rapid study of processing parameters, compared to what can be investigated experimentally.



Dry Carbon PW-30-70K
Frictional response @ 25 C, 100Kpa and 0.5 mm/min

Prepreg - BMS8-256
Frictional response @ 50 °C, 300Kpa and 0.1 mm/min

Figure 1: Sample comparison between the load trace for a dry woven fabric and a prepreg woven fabric. Coulomb friction model clearly overestimates the initial frictional response for the prepreg case. (Similar trend were reported for unidirectional prepregs [7].)

The present work is part of a longer-term research program at the Composites Research Network (CRN) aiming at a new modeling framework to predict the forming pattern of thermoset prepregs over double curvature surfaces, with an emphasis on capturing localized fiber-path defects during forming and consolidation stages. The sections to follow begin with a description of the proposed mixed lubrication model capturing the frictional response at the early stages of the processing (i.e. pre-gelation) when the resin behaves as a liquid by using flow-compaction analysis capabilities of composites process modeling software COMPRO [12] in the commercial finite element software, ABAQUS. Subsequently, the capability of the developed framework on capturing the mixed lubrication will be demonstrated as a case study on inter-ply friction experiments of a unidirectional prepreg material system.

2 METHODOLOGY

2.1 A mixed lubrication model for the pre-gelation stage of composites processing

During the consolidation of prepreg materials in the autoclave, the resin flows through the pores between the fibers when percolation flow is dominant and the resin excess is squeezed-out allowing the compaction of the material which attains the maximum fiber volume fraction. Throughout the stage at which the fiber volume fraction is reaching the final value of 50-70%, individual layers may slide over one another in order to accommodate the excess length dictated by the tool geometry, therefore, inter-fiber spacing becomes of the order of microns or smaller. The external pressure is initially supported by the resin and, as bleeding progresses, the pressure is transferred to the fiber bed. This process continues until the composite reaches the maximum compaction of the fibers for the applied external pressure and no more resin can be squeezed-out. The load carried by the fibers becomes appreciable for fiber volume fractions in the range 60 to 70%, [13]. From this point, the frictional behavior becomes heavily dependent on the load sharing by the resin and the filaments.

The concept of tribology may be a promising route to delve deeper into this problem and arrive at a more systematic modeling framework. Ideally, a physics-based definition of inter-ply friction capable of handling the transition between boundary lubrication, mixed lubrication, and full hydrodynamic state is of interest to cover the entire range of a material processing window. Understanding the various lubrication regimes provides insight into the various materials and processing parameters influencing inter-ply friction. Similar to the design of journal bearings, lubrication theories can be employed to study the effects of friction in composite forming, as the resin matrix at certain temperatures and strain rates can act as a lubricant between prepreg layers. The Stribeck curve provides an overall view of friction variation in the entire range of lubrication [14]. As illustrated schematically in Figure 2a, the curve provides a graphical representation of the friction coefficient, μ as a function of the Hersey number H, a non-dimensional quantity that is dependent on the dynamic viscosity of the lubricant film η, velocity v, and the Normal force N, categorizing the curve into three regions based on the level of contact between the plies or surfaces of interest, namely, boundary lubrication region in which Coulomb friction is dominated, hydrodynamic lubrication, where shear deformation of the fluid film is dominant, and mixed lubrication which is a combination of the two modes. The onset of fiber entanglement is the state where the frictional response falls into the mixed lubrication zone [7]. A thorough understanding is required to chart this region, not only under both the hydrodynamic and boundary lubrication zones, but also for the influence of surface topography on resin behavior, and the influence of contact and fluid pressure on the surface topography of plies. As depicted in Figure 2b, the extent of fiber-fiber interaction can vary depending upon the height of the resin layer, h, highlighting the significance of film thickness prediction which can be considered a *dynamic* phenomenon, given the sliding movement of plies over each other.

For developing the mixed lubrication model, it is important to couple the fiber bed compaction response and fluid lubrication model to address load sharing in the interface of contact. A common approach to model mixed lubrication is to calculate the contribution of frictional forces on the dry and lubricated regions and subsequently superimpose the coulomb frictional force between the intersecting filaments and the shear force of the resin film:

$$F_{Total} = F_{Fiber} + F_{Resin} \tag{1}$$

For the dry fiber part, the frictional force can be obtained as:

$$F_{Fiber} = \sum_{i=1}^{N} \iint_{A_{Fiber}} \tau_{Fiber} \, dA_{Fiber} \tag{2}$$

Where the Coulomb friction is governed according to Eq. 3 in which τ_{Fiber} is the shear stress, μ is the coefficient of friction, and N_{Fiber} is the normal force to the friction interface:

$$\tau_{Fiber} = \mu N_{Fiber} \tag{3}$$

The applied tangential load on the fluid portion can be obtained as:

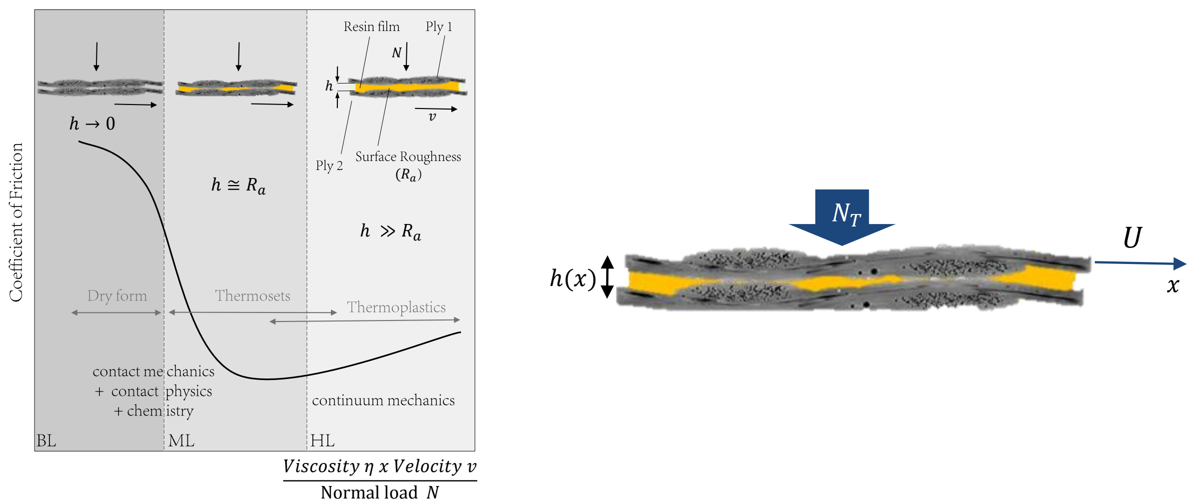
$$F_{Resin} = \sum_{i=1}^{N} \iint_{A_{Resin}} \tau_{Resin} \, dA_{Resin} \tag{4}$$

For hydrodynamic friction, as given by Eq. 6, shear stress is governed by the shear stress of the resin film, τ_{Resin} [11] where, η is the viscosity of the fluid, h is the thickness of the fluid film, and U is the velocity of one surface over the other.

$$\tau_{Resin} = \int_{-L}^{L} \eta U \,/h + h/2 \frac{\partial p_{Resin}}{\partial x} \tag{5}$$

Summing both fiber and fluid parts the total force can be calculated:

$$F_{Total} = \mu_{Fiber} N_{Fiber} + \iint_{A_{Resin}} \tau_{Resin} \, dA_{Resin} \tag{6}$$



(a) (b)

Figure 2: Generalized Stribeck curve [15] with the three regions of lubrication; from left: Boundary lubrication (BL), mixed lubrication (ML), and hydrodynamic lubrication (HL); h and R_a refer to resin film thickness and surface roughness, respectively; (b) Schematic representation of film thickness and separation of two unit cells with the resin layer (shown in yellow) for typical fabric prepregs.

In order to solve Eq. 7, N_{Fiber} and resin film thickness, h are required. During the compaction, the composite part is compressed through the thickness, leading to multiple fibre-to-fibre contacts when consolidation forces are applied during processing. According to Terzaghi's law, at any point in the laminate, the normal stress is given by the following expression [16]:

$$P_{Applied} = \overline{\sigma} + P_{Resin} \tag{7}$$

Where $P_{Applied}$ is the total applied stress, P_{Resin} is the resin pressure, and $\overline{\sigma}$ is the fibre bed effective stress. The resin flow through the channels of the plies can be described by Darcy's law by means of the permeability parameter which establishes the relationship between the flow rate and the pressure gradient necessary to drive the flow. Assuming the composite material as a void-free fibre bed fully saturated with a thermoset resin, the effective stress model implemented in COMPRO can be applied to extract the hydrostatic resin pore pressure between the layers, assuming a uniform pressure distribution of the resin underneath the filaments for the time being. The film thickness is then can be obtained using the thin lubrication theory approach employing a 1D steady state Reynold's equation [15]. For a laminar and transient flow of an incompressible, isothermal and viscous lubricant, the Reynolds equation can be written as :

$$\partial /_{\partial x} \left(\frac{h^3}{\eta} \cdot \frac{\partial p_{Resin}}{\partial x} \right) = 6U \frac{\partial h}{\partial x} \tag{8}$$

Where h is the film thickness, p_{Resin} the resin pressure, η the dynamic viscosity, and U the velocity in sliding direction. Since, in most cases, no analytical solutions for any of these equations exist, a numerical solution is necessary. In a given consolidation scenario, Reynolds numbers will be low due to the small gap height; hence inertia effects can be neglected. Also, the pressure variations in the through thickness direction can be considered negligible compared to those in the plane of the resin film. Considering the low deformation rate during the autoclave processing, the pore resin pressure can be converted to a semi-elliptical pressure distribution over the length of the contact area to account for flooded boundary conditions the inlet/outlet ($P(-L) = 0$; $P(L) = 0$; $\frac{\partial P}{\partial x}(L) = 0$), as shown in Figure 3.

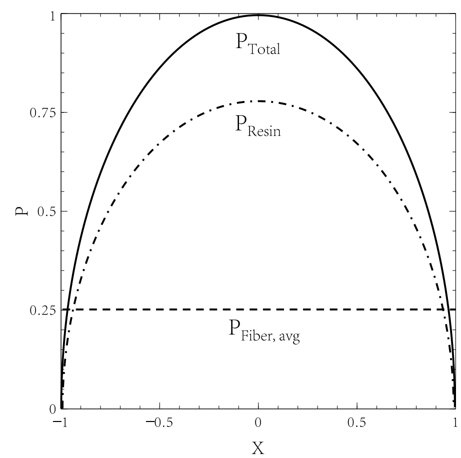


Figure 3: Dimensionless pressure distribution in the mixed lubrication regime [17].

Determining the homogenized film thickness using Eqs. 7 and 8, the friction force, F_{Total} can be found by superimposing the friction force at the interacting asperities and the shear force of the hydrodynamic component (Eq.1).

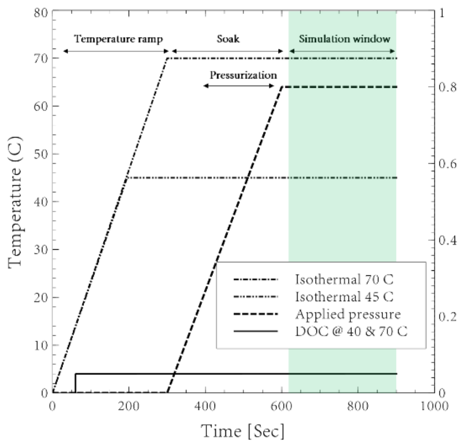
3 CASE STUDY

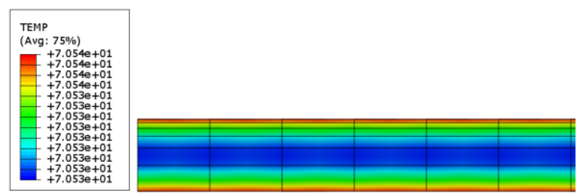
In this case study, ply/ply friction experiments, originally conducted by Larberg et al. [7], were adapted and verified for the proposed lubrication model in the previous section. The experiments we conducted on uncured AS4/8552 Unidirectional carbon fiber plies compacted to a pressure of 80 kPa and temperatures of 45 °C and 70 °C at 0.1 mm/min deformation rate. The test conditions are listed in Table 1. Material properties (resin viscosity and fiber bed compaction response) were obtained from [18, 19].

Table 1: Test conditions used for inter-ply friction experiments.
(Viscosity data were adapted from Larberg et al. [7])

Temperature (°C)	45 vs. 70
Viscosity (Pa s)	1000 vs. 180
Rate (mm/min)	0.1
Pressure (kPa)	80
Uncured ply thickness (mm)	0.203
Area (mm^2)	100 × 90

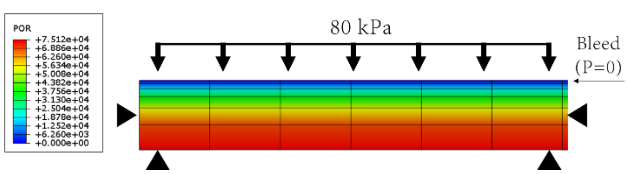
Figure 4a shows the temperature and pressure cycles defined in COMPRO to obtain the distribution of resin pressure for the inter-ply friction experiments. As expected, at such low temperatures, the degree of cure is substantially low and therefore no cross-linking occurs. A window of 600-900 seconds was selected to extract the pressure distribution after temperature soak at the desired temperature and pressurization to the desired compaction level (80 kPa), which marks the beginning of pull-out experiments. As shown in Figure 4b, a negligible temperature gradient also exists in the two-ply stack due to the small thickness of the specimen which is a necessity to capture the isothermal frictional behavior at various processing parameters. Figure 5a illustrates the final state of resin pressure at 70 °C. A bleeding boundary condition (P_{Resin}=0) was applied to the top surface of the stack. The resin flow starts from the top and gradually spreads into the interior region of the part. Correspondingly, the applied pressure starts to be shared by the fiber bed, and it develops gradually from the top to the bottom. For such low compaction pressure (as opposed to 700 kPa inside the autoclave), the proportion of effective fiber bed stress to resin pressure was found to be low. The magnitude of steady state shear stress for both fiber and resin is plotted in Figure 5b. The sudden drop in viscosity does not seem to change the contribution of fiber bed at 80 kPa, indicating the dominance of hydrodynamic lubrication at these test conditions.

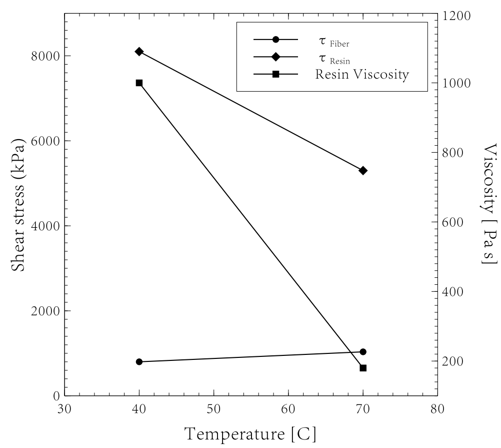




(a) (b)

Figure4: (a) Pressure, temperature cycles, and degree of cure (DOC) for thermochemical and flow-compaction simulations; (b) Temperature distribution through-the thickness for the 70 °C experiment. A minimal temperature gradient can be observed in the stack.

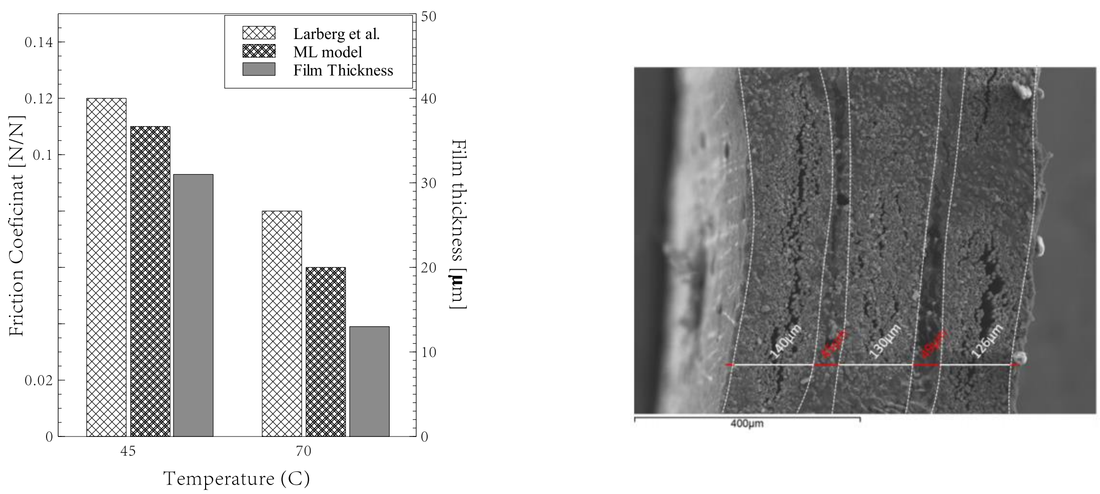




(a) (b)

Figure5: (a) Resin pressure distribution after soak and pressurization steps at t=800sec, 80 kPa and 70 °C; (b) Change in shear stress between fiber bed and resin for 45 °C and 70 °C inter-ply experiments along with the evolution of resin viscosity.

The friction coefficients at fixed temperature and normal pressure of 80 kPa are plotted in Figure 6a. The graph contains both the experimentally determined values and the values calculated by the mixed lubrication (ML) model along with the calculated film thickness. The experimental results indicate that below 70 °C, friction is still at the HL region of the Stribeck curve. It is expected that a further decrease in viscosity would reduce the film thickness, leading to the onset of fiber entanglement. While no reliable and reproducible experimental results on the film thickness are available to date, the capability of the model in capturing the experimentally observed trends of the frictional properties gives confidence to the proposed methodology. However, since the mixed lubrication mechanics involve fluid flow in the rough surfaces, the fluid flow equation must be addressed with sufficient ingredients of rough surface features. Although for the analyzed test results in this work the effect of surface roughness seems to be less significant due to the relatively sufficient thickness of resin film at the interface. Nonetheless, the assumption of uniformity of this film thickness remains to be crude even at higher viscosities, without considering the height distribution of the individual filaments at contact, as can be seen in Figure 6b.



(a) (b)

Figure 6: (a) Comparison between friction coefficients at yield: Mixed lubrication model versus experiments; (b) Cross-sectional image of three uncured unidirectional plies of 8552/AS4 taken at 300x magnification. Distinct regions of fiber and resin can be seen in a non-uniform fashion, which contribute to the material behavior in very different ways when under the influence of heat, pressure, and deformation [20].

4 CONCLUSION

Inter-ply friction can have a major influence on the final geometry of composite components, as the state of friction dictates the magnitude of the slippage between the plies during the cure cycle. A new methodology is briefly presented in this paper to calculate the inter-ply frictional properties, solely based on the rheological properties of the matrix constituent and the fiber-bed compaction response. One of the advantages of the model is that the film thickness can be predicted from the normal pressure and velocity. This avoids the use of some arbitrary thickness of this lubrication film, or the need for complex iterative numerical trials. The performance of the model was evaluated through a FE-based case study. The predictive capability of the mixed lubrication model and the significance of considering both the fiber-fiber interactions and hydrodynamic resin lubrication simultaneously on the final state of stress frictional response were demonstrated through comparisons to experiments. The preliminary predictions yielded encouraging results and showed the potential of the current mixed lubrication model to capture the proportionality of the contribution of fiber bed and resin on the frictional response at the ‘pre-gelation’ stage of composites processing; yet more accurate geometry and surface roughness measurements are required for more comprehensive analysis. The model is currently being investigated on thermoset fabric prepregs for further detailed validation. The predictive model resulted from this research can be used as a stand-alone tool or as part of a larger numerical predictive model, such as finite element simulations to assess the effect of ply slippage in the generation of fiber path defects in multi-layer consolidation scenarios.

5 ACKNOWLEDGMENTS

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