MANUFACTURING EFFECTS ON CURE CONSOLIDATION IN FILAMENT WOUND COMPOSITE STUCTURES

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SUMMARY: Cure consolidation is the primary cause of warpage in filament wound closed-section parts. The amount of consolidation that occurs is dependent on various manufacturing parameters including: winding tension, material system, cure profiles, and tooling stability. A methodology has been developed to predict and reduce the warpage based on the magnitude and profile of the consolidation [1]. To allow for use of this theory in commercial manufacturing environments the consolidation must be better characterized. The dominant manufacturing parameter is winding tension, which effects the final consolidation in two ways. The first being the winding lay-down thickness and the second being the Effective Cure Pressure. This paper investigates the latter effect. It will be shown from theoretical derivations and testing, that the winding tension does affect the level of consolidation and causes a non-linear strain profile through the laminate thickness.

KEYWORDS: Cure Consolidation, Filament Winding, Fiber Placement, Manufacturing, Warpage, Spring-Back.

INTRODUCTION

Warpage in composite parts is a serious problem across the manufacturing spectrum. The warpage is the result of residual stresses induced during manufacturing. In many cases the warpage after manufacturing, often referred to as *"spring-back"*, *"spring-in"*, or simply *"spring"*, can be large enough to make the part unserviceable. This is especially true in relatively large thin composite shells that are separated or sectioned after cure. This is commonly found in filament winding and fiber placement processes. In these cases the tooling is generally in the form of a male plug that has the composite fibers filament wound or fiber placed on the outer surface. These parts are considered "closed-sections" due to their geometry and because they can support internal fiber tension before cure. After the closed-sectioned parts cure they are generally cut axially or sectioned to allow for separation from the tooling. This is when deformation occurs.

To control the warpage problem the process of tool iteration is commonly used to get a usable final part. In this process a tool with the required final geometry is created and a part produced. The *spring-back* or *spring-in* that develops is then measured. Based on this a new tool is produced and the whole process is iterated until a usable part is obtained. It is easily seen that this is prohibitively expensive on large-scale structures. It also greatly restricts future design modifications since any change in geometry, material systems, fiber stacking sequence, or fiber orientation will start the iterative process anew.

Work being done at the Air Force Research Laboratory has resulted in *spring* measurements in excess of 10 times that predicted by recent *spring* theories [2, 4, 5]. It has been determined that the residual stress responsible for these large distortions are caused by cure consolidation incurred during manufacturing. All composite parts experience a degree of consolidation during cure. Autoclave curing, which is common in aerospace applications, exhibits this to a high degree. This consolidation along with any pre-existing winding or tooling Coefficient of Thermal Expansion (CTE) induced strain will result in residual stresses in the laminate. Automation of composite part fabrication greatly exaggerates this problem by allowing the fiber to be placed on the tooling at elevated tensions, leading to a large strain gradient through the laminate. These are always tensile strains since they cannot exhibit compressive stress of any significant value. If during cure, the strain relief becomes compressive the individual fibers will simply buckle. This is the result of the matrix being uncured or in a liquid state at the time of consolidation.

A model based on the consolidation has been developed and accurately predicts the *spring* [1, 3]. This model predicts the residual stresses by accounting for the change in arc length that a differential element, within a shell laminate, experiences during cure, Fig 1.

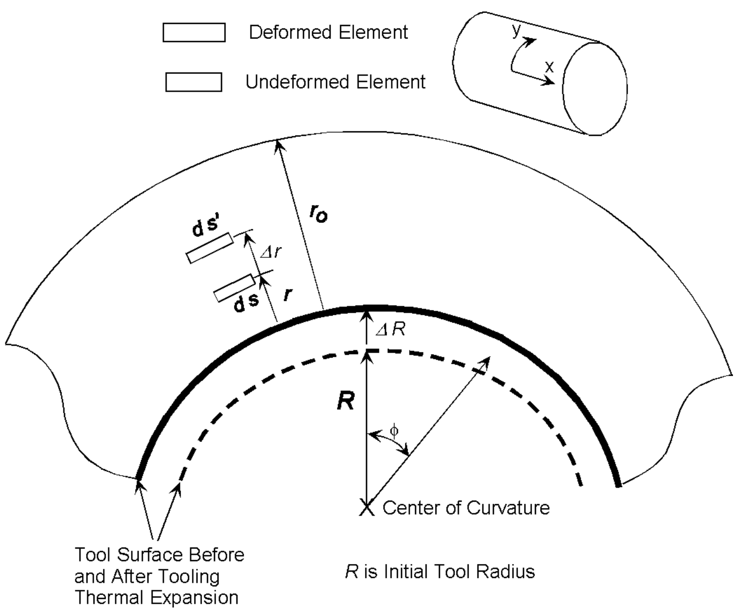

Fig 1: Shell Drawing Representing Cure Consolidation.

The strain profile resulting from the consolidation is

$$\varepsilon^t{}_1(z) = \varepsilon^t{}_{1o} - \Delta t\alpha_f + \left\{\Delta t\alpha_t + \frac{T(z + r_o(1+T)/2)}{R + z + r_o(1+T)/2}\right\} Sin^2\theta \quad (1)$$

where $\varepsilon^t{}_{1o}$ is the strain caused by the winding tension, Δt is the temperature change during cure, α_i is the CTE of the fiber and tooling, T is the percent consolidation, θ is the wind angle relative to the x axis, and z is measured from the laminate mid-plane [1, 3]. In general, Δr will be negative for consolidation. The equation for transformation between the r reference frame shown in Fig. 1 and the standard classical laminate theory reference frame is

$$r = z + \frac{r_o + \Delta r_o}{2} \quad (2)$$

where r_o is the pre-cure laminate thickness, and the post-cured laminate thickness is $h = r_o + \Delta r_o$.

This strain profile is responsible for the resulting *spring*. For this model to be implemented successfully, a thorough understanding of the scaling effects of the consolidation must be understood. Our goal in this paper is to gain a better understanding of the magnitude of cure consolidation and how manufacturing parameters contribute. This will allow for prediction of residual stresses within a laminate and lead to either elimination or reduction of these stresses, and ultimately result in decreased spring and better material performance.

The majority of cure consolidation in composites results from resin bleed-out and evacuation of entrapped air (voids). The magnitude of the consolidation is dependent on manufacturing parameters including cure pressure, winding tension, CTE, and material system characteristics (e.g., pre-preg fiber volume fraction, resin viscosity, etc.). In this paper the winding tension effects are investigated. Winding tension has the largest effect on the final magnitude of consolidation and actually contributes in two ways. The first being the winding lay-down thickness and the second being the Effective Cure Pressure. The winding lay-down thickness relates to how well the fibers are placed during manufacture. The more accurately the fibers are placed the less air will be entrapped, resulting in less consolidation during cure. The effective cure pressure is the amount of pressure a laminate experiences during cure. This paper investigates the latter effect. To characterize the consolidation, tests were conducted on flat plates at various cure pressures. Using this data an empirical model was developed to predict the consolidation for cylindrical sections. This model allows for prediction of consolation on full-scale part based on testing at the coupon level.

EFFECTIVE CURE PRESSURE

Filament wound structures are normally of the closed-section type. Because of this they are able to maintain tension in the fiber before the matrix has set. This tension can come about in two ways: winding tension, which may be constant or varied, and tension derived from tool-part CTE matched. This tension, or strain, that the fiber experiences will cause an increase in the consolidation as demonstrated with the higher CTE stainless steel tooling [1]. This is because the strain acts to increase the ECP, which is to say, it appears to the part as if a higher autoclave pressure is being used. This effect must be included for accurate characterization of the consolidation. To accomplish this we will develop a simple model to account for the fiber strain and its effects on the cure consolidation. We define this effect as the *Effective Cure Pressure* (*ECP).*

Derivation

The ECP is essentially the summation of the pressures on a particular lamina. In this context each lamina will have a different consolidation factor, *T*, so in fact we now have *T=T(r)* or *T=T(z)* depending on reference frame. To start our analysis we will assume that the effective cure pressure is dependent on the autoclave pressure and the pressure effects from the fiber strain, or

$$P^e = P^a + P^{strain} \tag{3}$$

We will ignore the autoclave pressure for now and concentrate on the strain-induced pressure. Assuming thin shell, the hoop stress in a cylinder is

$$\sigma_h = \frac{P(R+r)}{t} \tag{4}$$

where, R is the radius of the tooling, r is the distance from the tooling face to a specific lamina, and t the lamina thickness. In our case we know the stress but not the pressure, so substituting P^{strain} for the pressure and rearranging gives pressure as a function of the hoop stress.

$$P^{strain} = \frac{\sigma_h t}{R+r} \tag{5}$$

In a general laminate there exists N lamina and each will exert a pressure on the lamina below equal to Eqn 5. This is shown in Fig. 2. The total cure pressure on the k^{th} lamina resulting from the hoop stresses will be the summation of the pressures above, or

$$P_k^{strain} = \sum_{i=k+1}^{N} \frac{\sigma_{h,i} t}{R+r_i} \tag{6}$$

When the consolidation occurs the matrix has not set and there is no Poisson's effect in the global sense. The stress-strain relationship for the hoop stress is then simply

$$\sigma_h = \varepsilon_1 E \tag{7}$$

Substituting into Eqn 6 gives

$$P^{strain} = \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R+r_j} \tag{8}$$

where $\varepsilon_{1,\mathrm{j}}$ is the fiber strain in the *1*, or fiber direction, in the j^{th} lamina resulting from the winding tension. Eqn 8 is for hoop wound rings, for off-axis lamina a correction must be made. The total ECP including the autoclave pressure and assuming thin shell is

$$P^e = P^a + \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R} Sin^2\theta_j \tag{9}$$

where $\varepsilon_{1,j}$ includes both the winding tension induced strain and the strain resulting from any tooling/part CTE mismatch. The ECP can now be calculated and used to predict the consolidation of a filament wound structure.

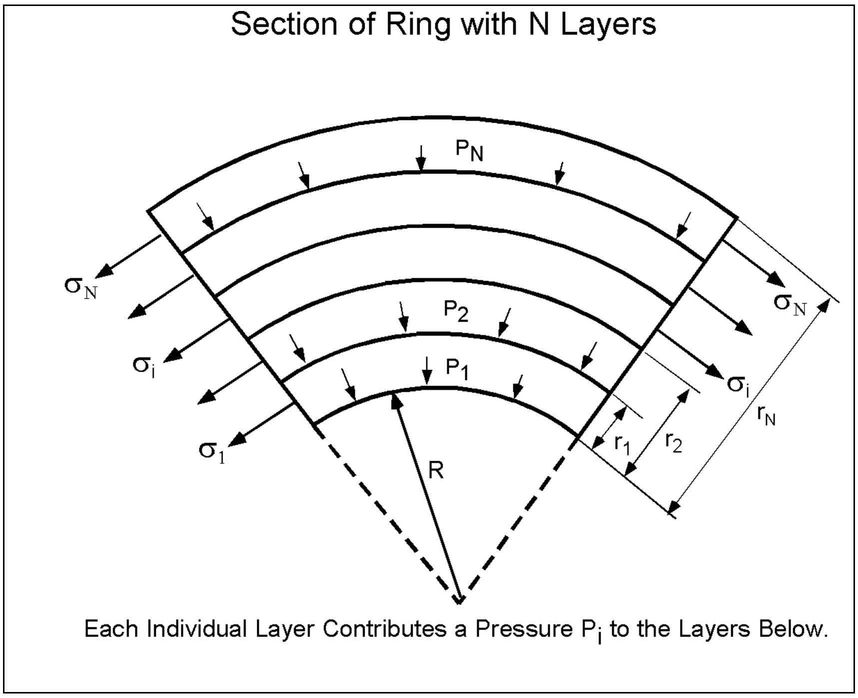

Fig. 2: Lamina with Fiber Strain induced Cure Pressure

Empirical Consolidation Approximation

Based on past experience and testing an empirical approximation is developed to predict the consolidation utilizing the ECP. The approximation is supported by comparison to data later in this paper. We first assume the consolidation behaves like a second order polynomial function over the pressure range of interest

$$T(P) = T_o + b\,P + c\,P^2 \tag{10}$$

From intuition we can further assume there must be a maximum pressure, P_{max} at which the laminate will have no more excess resin or entrapped air to bleed off and any additional pressure will result in no increase in consolidation. The laminate will become incompressible and the maximum consolidation corresponding to P_{max} is defined as T_{max}. At this point it also appears logical to assume that for zero pressure the consolidation will also be zero. Testing will show that this is not the case and with no pressure there will be a relatively small consolidation equal to T_o. Utilizing the boundary conditions,

$$\begin{aligned} &T(P_{\max}) = T_{\max} \\ &\frac{\partial}{\partial P} T(P_{\max}) = 0 \\ &T(0) = T_o \end{aligned} \tag{11}$$

the constant coefficient terms can be solved for,

$$b = \frac{2(T_{\max} - T_o)}{P_{\max}}$$
$$c = \frac{T_o - T_{\max}}{(P_{\max})^2} \tag{12}$$

where T_o, T_{max}, and P_{max} must be determined from testing.

This leaves us with a simple equation representing the consolidation with constant coefficients that can be obtained from testing. This form significantly increases the difficulty of predicting the spring when compared with the previous constant consolidation assumption [1]. This is because the consolidation is no longer constant but depends on the pressure, which in turn depends on the fiber strain, which depends on the consolidation. This is a circular argument with a direct closed form solution not possible. We are now left with a problem that must be solved in a computer iterative fashion. This is the main reason why the initial solutions were obtained with the assumption of constant consolidation.

Displacement Model

Utilizing the empirical approximation and the Effective Cure Pressure models discussed above we will now develop a model that predicts the displacement of a lamina, or a point, within a filament wound laminate. In this development we are no longer assuming the consolidation is constant, but depends on the ECP. The movement of a deferential element at any point within the laminate is

$$\Delta r(P) = \int_0^r T(P)dr \tag{13}$$

Substituting the empirical representation for consolidation, Eqn 13 gives

$$\Delta r(P) = \int_0^r (T_o + b\,P + c\,P^2)dr \tag{14}$$

In this case we are looking at a ring with finite thickness so the cure pressure is actually the effective cure pressure and a function of *r*.

$$\Delta r(r) = \int_0^r (T_o + b\,P(r) + c\,P(r)^2)dr \tag{15}$$

For a laminate each layer may be wound with a different tension so the ECP cannot be expressed as a continuous function. The solution must be looked at in a ply-by-ply fashion and the displacement of the kth lamina must be found by summing the consolidation of the lower layers.

$$\Delta r_k = \sum_{i=1}^{k} \int_{r_{i-1}}^{r_i} (T_o + b\, P_i^e + c\,(P_i^e)^2)\, dr \tag{16}$$

This equation can be integrated to give the displacement of the kth lamina.

$$\Delta r_k = \sum_{i=1}^{k} (T_o + b\, P_i^e + c\,(P_i^e)^2)(r_i - r_{i-1}) \tag{17}$$

At this point a substitution for the cure pressure, Eqn 9, is made.

$$\Delta r_k = \sum_{i=1}^{k} \left\{ T_o + b\,(\mathrm{P^a} + \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R} \mathrm{Sin}^2\theta_{\mathrm{j}}) + c\,(\mathrm{P^a} + \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R} \mathrm{Sin}^2\theta_{\mathrm{j}})^2 \right\} (r_i - r_{i-1}) \tag{18}$$

Eqn 18 represents the displacement of the k^{th} lamina resulting from both the autoclave and strain induced pressure. As stated before this equation cannot be solved for directly since the strain $\varepsilon_{1,\mathrm{j}}$ is dependent on the displacement Δr_k by,

$$\varepsilon_1^{\,t}(r) = \varepsilon^t{}_{1o} + \frac{\Delta r}{R + r} \tag{19}$$

where $\varepsilon^t{}_{1o}$ is the strain resulting from the initial winding tension [3].

The solution must be obtained by assuming an initial fiber strain and then iterating Eqn (18 & 19) for each lamina until the solution converges. First, a reference frame change is made to allow for use in classical laminate plate theory. Utilizing Eqn 2, the displacement of differential element within a laminate is

$$\Delta r_k = \sum_{i=1}^{k} \left\{ T_o + b\,(\mathrm{P^a} + \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R} \mathrm{Sin}^2\theta_{\mathrm{j}}) + c\,(\mathrm{P^a} + \sum_{\mathrm{j=k+1}}^{\mathrm{N}} \frac{\varepsilon_{1,\mathrm{j}} E_j t_j}{R} \mathrm{Sin}^2\theta_{\mathrm{j}})^2 \right\} (z_i - z_{i-1}) \tag{20}$$

where z is measured from the laminate mid-plane. Utilizing an iterative program and the solution for the ECP derived above, the residual strain profile within a laminated cylinder can be calculated. The iterative program is not discussed in detail here but the results are used later in the discussion of results.

EXPERIMENT OVERVIEW

A series of tests were conducted to verify the assumptions made above and to gather data needed for the investigation of the effects of ECP on filament wound closed-section rings. To mimic the ECP that occurs in filament winding, flat plate coupons were cured at different autoclave pressures. Since the ECP is simply the summation of autoclave and hoop stress induced pressures a wide range of ECP's could be estimated in this manner. Specifically, this test determined the T_o, T_{max}, and P_{max} required to obtain the constant coefficient terms in Eqn 10. Test were conducted at 1380, 965, 620, 345, and 172 kPa. The coupons were 7.62 x 10.16 cm. (3 x 4 in.) and made from Fiberite IM7/977-2 pre-preg carbon/epoxy resin system, Fig 3.

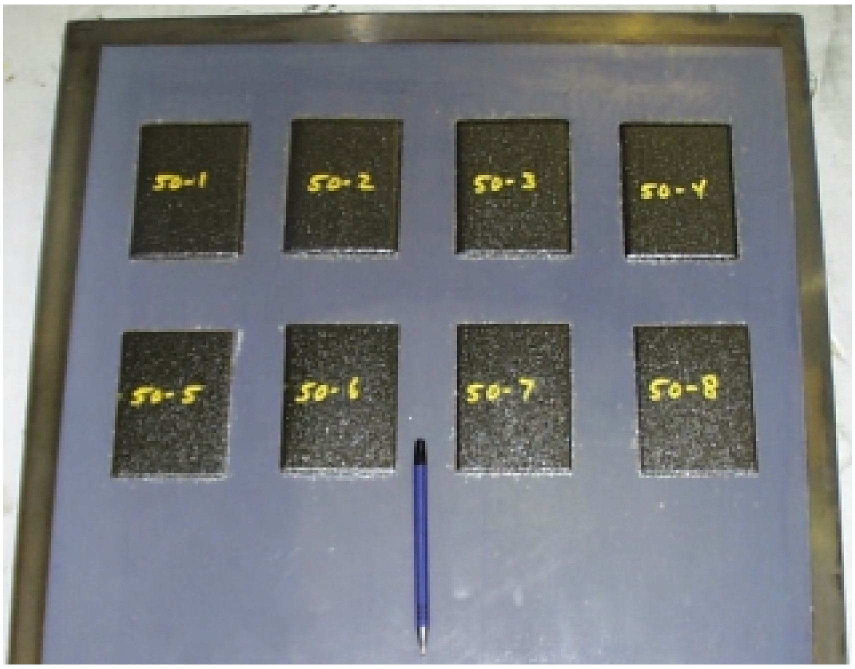

Fig. 3: Flat Panel and Cylindrical Test Specimens.

DISCUSSION OF RESULTS

As can be seen in Fig. 4, the match between the experimental and empirical consolidation predictions are very good. In this case the empirical data is the assumed consolidation, Eqn 10, with the coefficients found utilizing Eqn 12. This means that for a particular resin system the consolidation at any point within the laminate can be determined simply by knowing the ECP. It is interesting to note that for zero pressure there is still approximately 5% consolidation. This is due to the resin flow that takes place, regardless of pressure, when the resin is raised to the cure temperature. It is of academic interest only since in actual applications there will be a minimum of vacuum bag pressure applied to the part.

With this information an investigation can be made into the effects, if any, the ECP has on the consolidation of a filament wound part. Figure 5 shows the change in average consolidation for a representative filament wound cylinder utilizing 44 N winding tension, which would equate to a 138 MPa tow winding stress. As is expected the thicker laminates have higher consolidation. This is a result of higher ECP's. Also of interest is the converging of all curves for the higher pressures. This is the result of the maximum consolidation pressure being met by the autoclave pressure alone. If the autoclave pressure reaches P_{max}, the maximum consolidation will occur whether there is a hoop stress addition to the ECP or not. Because of this the additional complexity of taking into account the ECP in higher-pressure cure processes can be neglected. Above 500 kPa the error is less than 5 %. However, for lower-pressure cure processes, neglecting the hoop stress effects could result in errors greater than 30 %.

CONCLUSIONS

In this paper the consolidation occurring in filament wound closed-section parts was investigated. The goal was to better understand the effects of the additional cure pressure resulting from the winding hoop stress. A series of equations were developed to account for both these and the autoclave pressures.

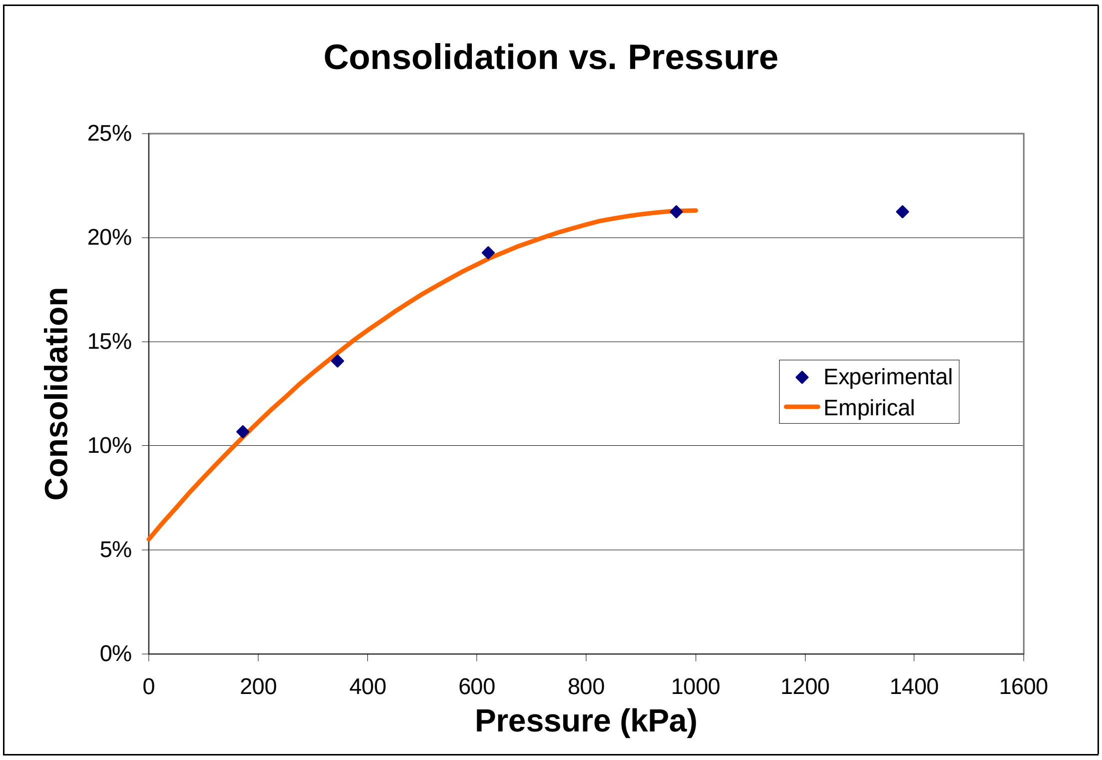

Fig. 4: Flat Panel Test Results

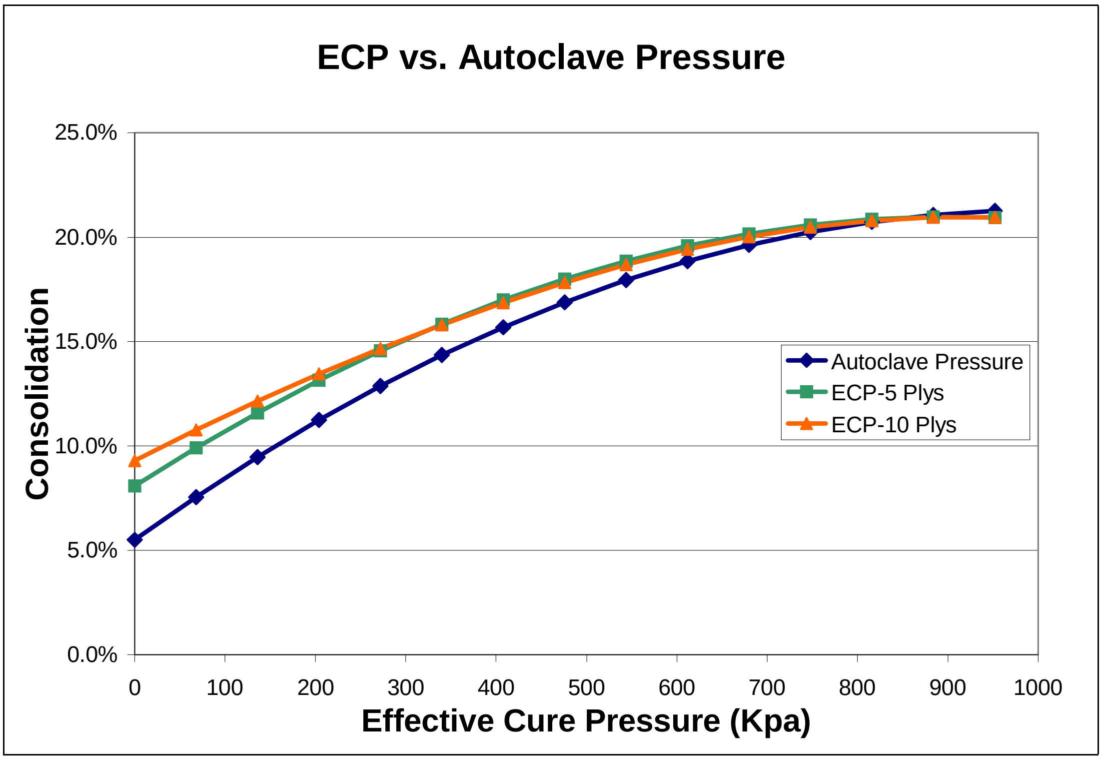

Fig. 5: Effective Cure vs. Autoclave Pressure Comparison

To accomplish this, assumptions were made relating the consolidation to the cure pressure. The accuracy of the assumptions and derived equations were then checked using coupon tests. It was found that the ECP does have a significant effect on the consolidation and that an empirical approximation can predict the consolidation. The effects of the ECP on a representative filament wound cylinder were then investigated. It was found that, for higher-pressure cure processes, the error caused from ignoring the ECP would be small, less than 5%. However, for lower-pressure cures, neglecting the hoop stress generated pressures could cause significant error, greater than 30%. Utilizing the equations developed for ECP, along with simple coupon testing, the consolidation of a filament wound cylindrical part can be determined. This simplifies the problem of predicting and measuring the consolidation of full-scale tooling.

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