A Proposed Method for Predicting the Load Resistance of a Particular Type of Ceramic Enamel Coated Glass

Authors

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1 Introduction

Over the past several years, there has been a relatively small number of highly publicized thermally induced failures of ceramic enamel coated glass as discussed elsewhere [1,2,3]. In at least one case, the thermal breakage was determined to be the result of improperly installed batt insulation placed directly behind the ceramic enamel coated spandrel units [3]. The writers are not aware of a single documented ceramic enamel coated glass failure as the result of uniform pressures. This notwithstanding, the publicity surrounding the thermal failures precipitated a major discussion within the controlling ASTM International Task Group as to whether ASTM E1300 [4] should be modified to incorporate strength reductions for ceramic enamel coated glass subjected to uniform pressures. This discussion has continued for almost a decade.

The effort to modify ASTM E1300 to reflect a reduced uniform pressure resistance of ceramic enamel coated glass appears to be driven by a realization that the bending strength of ceramic enamel coated glass is significantly less than the analogous strength of freshly manufactured glass with no ceramic enamel coating. This fact has been documented by a wide group of unrelated researchers [1,2,5,6,7]. European standards incorporate ceramic enamel coating strength reductions on the the order of 36 to 38 percent [8]. However, the point that is being overlooked by those proposing changes to ASTM E1300 is that the document reflects the strength of in-service glass and not freshly manufactured glass. It has been reported that the strength of in-service glass is as much as 50 percent less than the analogous strength of freshly manufactured glass [9]. The central question regarding possible revisions to the uniform pressure provisions of ASTM E1300 is whether strength reductions associated with ceramic enamel coatings are greater than strength reductions associated with in-service exposures.

In the most recent modification to ASTM E1300, a note is being added that advises the users of ASTM E 1300 that ceramic enamel coatings are known to affect glass load resistance. The note further advises the designer to consult the manufacturer for guidance. However, the ASTM changes offer no advice or guidance for manufacturers to make a rational judgment about the strength of their ceramic enamel product. The purpose of this paper is to provide a rational procedure that can be used to evaluate the strength of ceramic enamel coated glass plates subjected to uniform lateral pressures as deemed necessary.

2 Background

As stated above, the impetus for the reevaluation of the ASTM E1300 glass thickness selection procedure for ceramic enamel coated glass was the result of publicity associated with a few thermal stress failures. Thermal stresses induced in glass plates are usually associated with the effects of solar exposures. It is known that the level of thermal stress induced in a glass plate by a particular level of solar exposure is proportional to the absorption of the glass plate, i.e., the higher the absorption, the higher the thermal stress [9]. Further, it is known that the solar absorption of a particular type of glass generally increases as the thickness of the glass increases. Therefore, it can be concluded that the magnitudes of the thermal stresses induced in a particular glass plate by a given solar loading increase as the thickness of the glass increases.

In contrast to the thermal behavior of glass, it is known that the uniform pressure resistance of glass plates increases as the thickness of the glass increases. Thus, if changes are made to ASTM E1300 that require the thicknesses of ceramic enamel coated glass to be increased as the result of a nonexistent problem with uniform pressure resistance, the susceptibility of the ceramic enamel coated glass to thermal loadings will be increased. Despite this likely outcome, there continues to be a small group seeking to modify the ASTM E1300 uniform pressure design procedure to increase the required thicknesses of glass with ceramic enamel coatings. Care must be taken that a possible thermal stress problem is not exacerbated by an ill-informed modification to ASTM E1300.

3 Failure Theory for Ceramic Enamel Glass

Prior to the introduction of ASTM E1300, all glass thickness selection procedures dealing with uniform lateral pressures in the US were based on estimates of glass strength determined through the destructive testing of freshly manufactured glass plates. This early testing consisted of determining the uniform pressure required to break glass plates for a wide distribution of sizes, thicknesses, and aspect ratios [10]. These data were then analyzed to develop empirical relationships between the mean breakage pressure, size, and thickness of freshly manufactured glass. Design pressures were then developed by dividing the empirically derived mean breakage pressures by a suitable strength reduction factor intended to account for the statistical distribution of glass strength [9,11].

These early glass design efforts were focused on modeling breakage pressures rather than breakage stresses because it was not possible to properly calculate the stresses induced in rectangular glass plates until the middle 1970's. The main issue with calculating stresses in glass plates is that glass plates typically experience significant geometrically nonlinear behavior before breakage. Geometrically nonlinear analyses that are consistent with the unique boundary conditions associated with typically installed glass plates are not covered in traditional plates and shells texts. Therefore, the early US glass thickness selection procedures were forced to rely on empirically developed breakage pressure data and not breakage stress data.

PPG industries was the first major US glass manufacturer to use a geometrically nonlinear numerical analysis to develop relationships between uniform pressures and maximum stresses [12]. PPG combined results of this geometrically nonlinear plate analysis with a maximum stress failure theory to model the strength of freshly manufactured glass to develop the first US glass thickness selection charts based on breakage stress rather than breakage pressure [12,13]

Based on research conducted in the late 1970's and early 1980's it was determined that the in-service strength of glass is significantly less than the strength of freshly manufactured glass [9,14,15]. Once this was clearly established by independent researchers and widely accepted by the US glass industry, it was determined that glass thickness selection procedures should reflect the strength of in-service glass and not the strength of freshly manufactured glass.

In the 1980's, the in-service strength reduction premise was coupled with a newly developed glass failure prediction model that incorporated a geometrically nonlinear stress analysis [9,16,17] . The resulting procedure was then used as the basis for a new ASTM glass thickness selection procedure for glass plates exposed to uniform pressures. The original ASTM E1300 procedure reflected a 60-second load duration but this load duration was reduced to 3 seconds in the late 1990's in an attempt to conform with advancing US wind codes [9]. However, the premise of designing glass for in-service strength rather than its freshly manufactured strength remains the basis for the glass thickness selection procedures presented in ASTM E1300 [4].

It is known that the strength of glass is controlled by the characteristics and distribution of flaws across the surface of the glass. Full discussions of the relationship between surface flaws and glass strength are presented elsewhere [9,16]. The surface flaws that control the strength of in-service glass tend to be relatively severe and sparsely distributed across the surface of the glass [18]. As such, the strength of in-service glass is best modeled using a statistical approach such as the failure prediction model discussed above [16]. When such a statistical approach is used, breakage stresses vary with both the aspect ratio of the glass and the area of the glass, but the resultant stresses are substantially lower than design stresses for freshly manufactured glass.

A review of a large amount of failure strength data suggests that the surface flaws associated with the breakage of ceramic enamel coated glass are much more uniform in both severity and occurrence than is the case with in-service glass. As a result, one of the most common observations regarding ceramic enamel coated glass strength data is a characteristically low coefficient of variation for both breakage load and breakage stress. Further, the breakage stress of ceramic enamel coated glass does not appear to vary with plate area as is the case for in-service glass. Based upon these observations, the writers have recommended that the strength of ceramic enamel coated glass is best modeled with a maximum stress approach similar to that originally implemented in the historic PPG strength model.

4 Proposed Design Procedure for Ceramic Enamel Coated Glass

In a previous paper, the writers suggested that the uniform pressure design stress for a particular type of ceramic enamel coated glass could be established through the testing of a representative sample of beams with the same ceramic enamel coating and the same residual compression surface stress [19]. The previous procedure to establish the maximum design stress involved the testing of representative ceramic enamel beams, correcting the resulting failure stress data to the proper load duration, and then using statistical procedures to the establish the design stress corresponding to the desired probability of breakage. Then it was proposed that the experimentally determined design stress be used in conjunction with a geometrically nonlinear stress analysis to determine the acceptable uniform lateral pressure for a particular plate with the same ceramic enamel coating. Finally, it was proposed that the experimentally determined design lateral pressure be compared to the ASTM E1300 design pressure determined for glass plate with no ceramic enamel coating. The acceptable design pressure for the ceramic enamel coated glasss would be taken to be the smaller of the two values. [19]

While the originally proposed ceramic enamel design procedure continues to be valid as presented [19], it is believed that the procedure can be improved by introducing a term which is referred to as the net breakage stress, σ_{Net}.The net breakage stress is found by subtracting the residual compression surface stress, σ_{RCSS}, from the measured breakage stress, σ_{Net}, as follows.

$$\sigma_{Net} = \sigma_{Br} - \sigma_{RCSS} \qquad (1)$$

The standard deviation of a set of data is not affected by offsetting the measured data by a constant. This means that the magnitude of the standard deviation of the breakage stress data is the same as the standard deviation of the net breakage stress data. Thus, whether the normal distribution is applied to net stress or the breakage stress data, the ultimate design stress will be the same when the residual compression surface stress is added back in. The advantage of the net breakage stress approach is that it allows a designer to easily account for variations of residual compression surface stresses that may occur during the manufacturing process. Thus, results of one set of data for a particular residual compression surface stress can be applied to a set of glass plates with different residual compression surface stresses without the requirement for additional testing. This makes the revised ceramic enamel coated glass design procedure more versatile.

The originally proposed ceramic enamel design procedure is revised as follows.

1. Select a representative sample of ceramic enamel coated glass to be tested.
2. Use appropriate techniques to measure the residual compression surface stress, σ_{RCSS}, of the specimens.
3. Subject the beam specimens to a controlled four-point bending test to determine the measured breakage stress, σ_{Br}, associated with each specimen.
4. Calculate the net breakage stress, σ_{Net}, for each specimen.
5. Use standard load duration correction procedures to adjust the net breakage stress, σ_{Net}, for each specimen to a 3-second duration stress as incorporated in ASTM E1300.
6. Calculate the mean and standard deviations of the 3-second duration net breakage stress, σ_{Net}, data.
7. Use standard normal statistical procedures to determine the 3-second duration net design stress, σ_{ND}, corresponding to a probability of breakage of 8 lites per 1,000 as incorporated in ASTM E1300.
8. Add the net design stress, σ_{ND}, from the previous step to the applicable residual compression surface stress, σ_{RCSS}, to determine the design stress, σ_{D}, corresponding to a probability of breakage of 8 lites per 1,000.
9. Combine the design stress, σ_{D}, determined from the previous step with results from a geometrically nonlinear stress analysis to determine the allowable design pressure corresponding to breakage probability of 8 lites per 1,000 for the glass plate being designed.
10. Use the ASTM E1300 procedure for in-service glass to determine the allowable design pressure for a glass plate of the same geometry with no ceramic enamel coating.
11. The design pressure for the glass plate being designed is taken to be the smaller of the design pressures from steps 9 and 10.

The writers have previously presented data that can be used to demonstrate the use of the revised procedure for 6-mm glass with a ceramic enamel coating [19]. In this effort, a set of twenty 305 x 602 x 6-mm glass beams with ceramic enamel coatings were prepared for testing. The average residual compression surface stress for these specimens was determined to be approximately 45.5 MPa. This value is approximately 21.5 MPa above the minimum value of 24 MPa specified in ASTM C1048 [20] for heat-strengthened glass. It is common for glass manufacturers to provide glass that has a residual compression surface stress that is significantly greater than the minimum required.

The above ceramic enamel coated glass beams were tested to failure in a four-point bending machine. It was found that the mean 3-second duration breakage stress was 75.7 MPa with a standard deviation of 2.96 MPa. These values result in a coefficient of variation of about 3.9%. The corresponding value of the mean net breakage stress, $\boldsymbol{\sigma_{Net}}$, was found to be 30.2 MPa. The above values were combined with the normal distribution to determine that the design net breakage stress, $\boldsymbol{\sigma_{ND}}$, associated with a probability of breakage of 8 lites per 1,000 for this type of ceramic enamel coated glass is 23.1 MPa.

This design net breakage stress, $\boldsymbol{\sigma_{ND}}$, can then be used to determine the design pressure for a 1,016 x 1,524 x 6-mm heat-strengthened glass plate that has the same ceramic enamel coating as the beams that were tested. First it is assumed that the ceramic enamel coated glass being designed has the same residual compression surface stress as the beams that were tested. It can thus be found that the design stress, $\boldsymbol{\sigma_D}$, associated with a probability of breakage of 8 lites per 1,000 for this plate is 68.6 MPa. If this design stress is combined with a geometrically nonlinear plate analysis the design pressure for this glass plate can be determined to be 9.72 kPa. If the designer chooses to base the design pressure of the 1,016 x 1,524 x 6-mm heat strengthened glass plate on the minimum residual compression surface stress of 24 MPa as presented in ASTM C1048 [20], then the design stress, , becomes 47.1 MPa. If this design stress is combined with a geometrically nonlinear plate analysis the design pressure for this glass plate is determined to be 6.37 kPa.

The design pressure corresponding to a 3-second load duration with a probability of breakage of 8 lites per 1,000 for a glass plate with no ceramic enamel coating of the same geometry can be determined to be 5.27 kPa using ASTM E1300 [4]. It is thus seen that both the design pressure associated with the actual residual compression surface stress of 45.5 MPa and that associated with the C1048 minimum residual compression surface stress of 24 MPa are greater than the design pressure determined from ASTM E1300 assuming no ceramic enamel coating. Thus, the regular ASTM E1300 procedure for glass with no ceramic enamel coating controls for this situation. It has been found by the writers that in most practical cases, the design of ceramic enamel coated glass are controlled by the unmodified ASTM E1300 procedure [7].

5 Conclusions

There have been a relatively small number of thermally-induced glass failures that have led some to call for ASTM E1300 to incorporate special provisions for the design of ceramic enamel glass. While there is little to no evidence that would suggest there is a problem with the current ASTM E1300 uniform pressure treatment of ceramic enamel coated glass, the call for change has been debated within ASTM for almost a decade. If the glass thickness selection procedures incorporated in ASTM E1300 were based on the freshly manufactured strength of glass, it would be reasonable to incorporate a strength reduction provision for ceramic enamel coated glass. However, as previously stated, ASTM E1300 already incorporates a representation of in-service glass which has a strength reduction that is on the order of the strength reduction associated with ceramic enamel coated glass.

As a result of this decade long debate, ASTM E1300 is currently being amended to include a simple note stating that ceramic enamel coatings are known to affect glass load resistance. It is further being suggested in the revised ASTM standard that a glass designer contact the manufacturer for guidance associated with specific products. A procedure is presented herein that will allow a rational evaluation of the uniform pressure strength of ceramic enamel coated glass plates if a designer or manufacturer chooses to do so. This procedure is presented in terms of a net stress model that can be used to model the strength of ceramic enamel coated glass plates with a wide range of residual compression surface stresses.

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