Process simulation in LSDYNA from the viewpoint of a materials supplier: towards an integrated approach for performance and process

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1 Introduction

Electromobility and sustainability are the current megatrends that drive the market development of the automotive industry. In order to be conforming to these megatrends, one solution exists, and this is the lightweighting of automobile structures. More specifically, with advancing metal technology, the trend is for automotive Original Equipment Manufacturers to reduce the thickness of outer, non-load bearing panels of closures like doors and hoods. However, reducing the thickness of such panels creates an additional challenge, this being retaining both the Class A surface finish and the localized stiffness, which is crucial as it defines the experience of the end-user of the automobile. This can be achieved by leveraging 2D rubber or epoxy reinforcements that enable the bridging of the weight reduction and the localized stiffness competing requirements. Outer panel thickness reduction, however, makes them more prone to process induced permanent deformations due to temperatures of the oven required for curing coatings and paints.

The e-coat oven is a thermally demanding environment where the curing of the majority of 1 component adhesives and reinforcements takes place. Challenges vary and are related from thermal expansion coefficients mismatch to chemical induced stresses and the combined phenomena that take place there. Understanding on how a polymer cures during the e-coat oven permits to create informed design choices for that polymer product and of course reduce the potential defects that may occur because materials undergo a change of properties due to temperature, thermal expansion, deform due to the chemical reactions taking place during curing and all that while surrounded by the expansion of their substrates. These kinds of loading can be from mild to very severe, leading to premature failures of the joints or the plastic deformation of the substrates, which have the tendency to become thinner as the associated materials technology improves.

The present paper aims to demonstrate the whole process chain of simulations of such reinforcements, focusing onto process-induced effects. Henkel Ag & Co KgaA's position has always been to dedicate effort into developing simulation methods for internal but also external (customer) use that can facilitate the actual products' design and development, but also support its customers throughout their own simulation effort with best-in-class knowhow and engineering capability.

In what concerns scientific literature regarding the use of *MAT_277, the authors would like to acknowledge the investigations conducted by [1] where a very comprehensive guide on how to populate the data, along with experimental validation has been conducted, [2] where *MAT_277 was used to simulate Multimaterial adhesive joints and finally [3], where the material model has been used to work out process effects on a cationic photopolymerized epoxy adhesive.

It is to the authors' opinion that by leveraging simulation, decisions around products but also around application strategies can become more informed in order to bridge the sometime conflicting requirements for low weight, high aesthetics, and adequate stiffness.

2 Problem Description

For the purposes of this paper/presentation, the whole simulation cycle from conception to process simulation will be presented, using as basis a public domain Finite Element Analysis Model from the United States' National Highway Traffic Safety Authority. The model selected in the one of a Chevrolet Silverado and is developed for crash analysis but adapted to cover the needs of stiffness & process

simulation, to enable the performing of a holistic reinforcement exercise. Since this is a full car model, only the parts & components associated with the Front Right Door are retained.
Generally, the issue of process simulation has undergone a significant boost of interest throughout the years, especially after the introduction of curing material models in LSDYNA. Since for reasons of intellectual property no actual Finite Element model of a current technology vehicle can be presented, a public domain finite element model from the National Highway Traffic Safety Authority (NHTSA) is being used. This finite element model is developed for crash and is a whole vehicle model of a Chevrolet Silverado [1]. From the whole vehicle model available for download, only the front right door is used.
For the purposes of this study, two different products from Henkel AG & Co KgaA are investigated: a sprayable 2D structural reinforcement, namely Teroson RB 5185 applied in the area where stiffness is most degraded due to the panel thickness reduction and an antiflutter adhesive, namely RB3254, applied between the outer panel and reinforcement beams of the door. In Fig. 1, these are marked with the red color.
In terms of lightweighting, the thickness of the outer front door panel is reduced from 0.75 mm to 0.65 mm. The modal analysis capability of LSDYNA/Implicit is being used to identify potential areas with reduced local bending stiffness and then an initial survey took place to identify the areas where the stiffness drop is more prominent. Then, using a standard footprint of the applied reinforcement, the thickness needed to return the local stiffness to the full thickness equivalent is being investigated. Finally, after selecting the necessary thickness of the 2D sprayable reinforcement, the curing within the oven is simulated and potential remedies to the process induced (plastic) deformations are considered. A comprehensive list of the simulation runs is provided in table 1.

Analysis Type	**Purpose**
Modal analysis	Definition of positions of interest for stiffness assessment
Nonlinear statics analysis	Down selection of position of interest. Definition of performance target
Nonlinear statics analysis	Reinforcement thickness design
Nonlinear Dynamics	Process Simulation

Table 1: Types of analysis conducted and purpose in the study context.

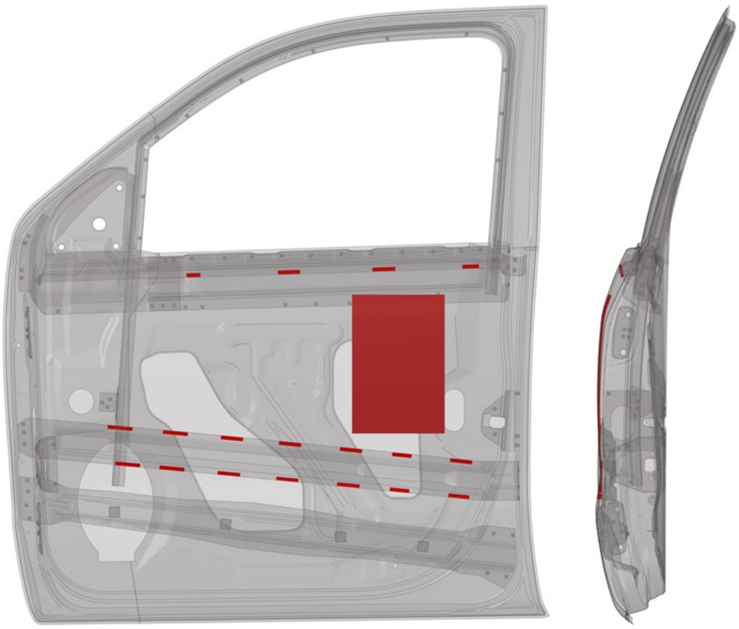

Fig.1: Finite Element Model of the Chevrolet SILVERADO door. Red denotes Henkel AG & CO KgaA applied products.

2.1 Structural mechanics material cards

For the structural analysis conducted, TEROSON RB 5185 was simulated using **`*MAT_024`** (**`*MAT_PIECEWISE_LINEAR_PLASTICITY)`**, while for TEROSON RB 3254 **`*MAT_1`** **`(*MAT_ELASTIC)`** was used. The input parameters for TEROSON RB 5185 have been calibrated via a combination of tensile testing and 3 Point Bending tests.

2.2 Process simulation material cards

Table 2 describes the tests used for populating the different parameters used for **`*MAT_277`** **`(*MAT_ADHESIVE_CURING_VISCOELASTIC).`** The decision for using **`*MAT_277`** and not **`*MAT_307`**, was based on the fact that the necessary method investigations and stability verifications before adopting the material card as standard is currently under way.

Subsystem of MAT_277	**Tests conducted**
Curing Kinetics	Differential Scanning Calorimetry (Ramped heating at 2°C/min, 4°C/min, 8°C/min, 10°C/min & isothermal heating conditions at 165°C, 175 °C, 185 °C)
Chemical Strains	Gravimetric testing for different heating times @ 175 °C
Coefficient of Thermal Expansion	Dilatometry
Viscoelastic behavior	Dynamic Mechanical Analysis with in-house software for the creation of mastercurves

*Table 2: List of tests conducted for the creation of the *MAT_277 material cards for TEROSON RB 5185 & TEROSON RB 3254*

One main assumption in the creation the material cards for the products involved has been that the products' CTE remain unaffected by the degree of cure.

2.3 Simulation Runs

2.3.1 Structural Analysis

Generally, indentors used for stiffness assessment throughout the industry vary. As a general approach, a cylindrical indentor with a diameter of 100 mm was used, since it was judged that it would pose a challenging load case. A smaller indentor in diameter would mean that a smaller reinforcement in footprint would need to be used. Fig. 2 depicts the placement of the indentor. In terms of loading, a 100N force was applied to the rigid indentor.

Fig.2: Indentor placement in relation to the Chevrolet Silverado door

The following analysis have been initially conducted:
- Baseline with a front panel thickness of 0.75 mm
- "As lightweighted" using a front panel thickness of 0.65 mm and no reinforcement.
- "Reinforced" with thicknesses of 2 mm, 2.5 mm, 3 mm & 3.5 mm over a footprint of 200 mm (along the car length direction) and 300 mm width.

2.3.2 Process Simulation

For the process simulation, the finite element model remained the same, without including the indentor. The thermal load imposed was uniform and not varying through the thickness of the door. Fig. 3 shows the thermal cycle used.

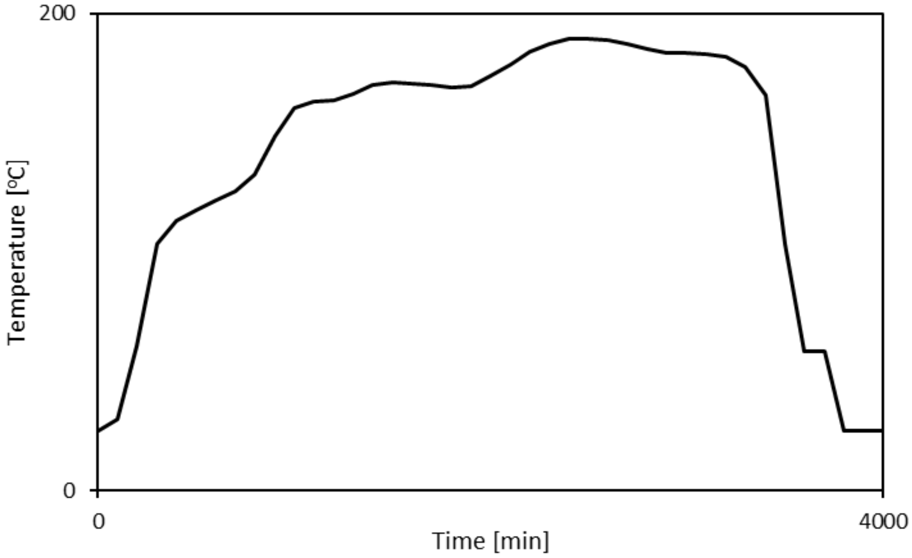

Fig.3: Thermal cycle used for process simulation.

2.3.3 Anti Readthrough application strategy

After the initial process simulation, an alteration of the deposition strategy of the sprayable reinforcement has been designed, to demonstrate that stiffness improvement can be retained, with decreased usage of material. After the static analysis conducted, a further process simulation run took place, in order to validate the reduced process induced deformations originating from application.
This application strategy involves applying the sprayable reinforcement in stripes with a 7.5 mm gap between them, as depicted in Fig. 4

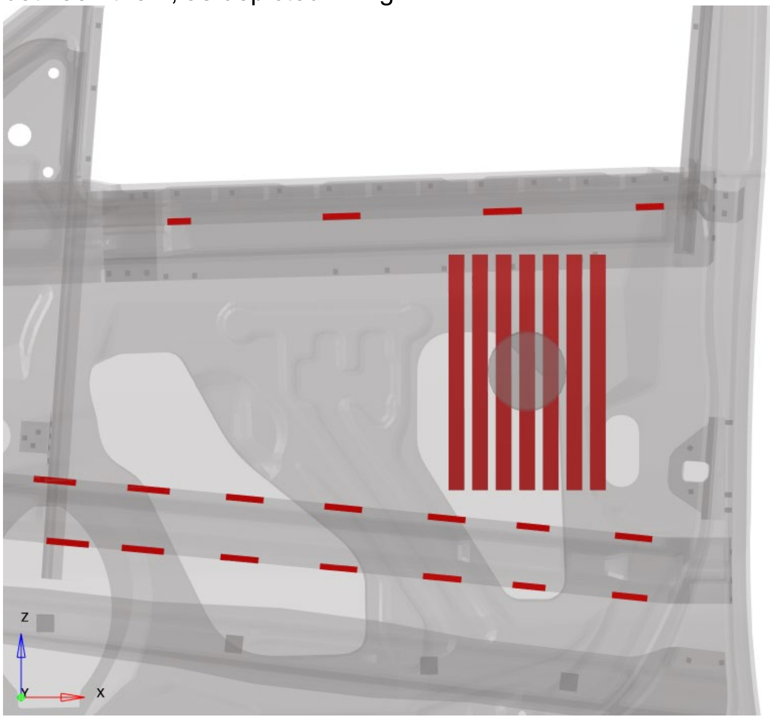

Fig.4: Anti-readthrough application method

3 Results and discussion

3.1 Stiffness improvement – results

Fig. 5 shows the Force-Displacement profiles for the initial set of structural analysis conducted, namely, the baseline, the unreinforced lightweighted panel, and the 4 different thicknesses of reinforcement. One can see that the displacement reached at the force level of 100N is significantly higher in the case of the “As lightweighted” but not reinforced case, namely it become 3.63 mm from 1.16 mm in the baseline case. The incorporation of TEROSON RB 5185 is significantly improving stiffness (reducing displacements at the 100 N force level), even at low thicknesses (2 mm). The baseline localized stiffness of the panel is reached -even slightly exceed – when the thickness of the reinforced is 3 mm. it should be noted that for all cases, the footprint remains 200 mm length and 300 mm width.

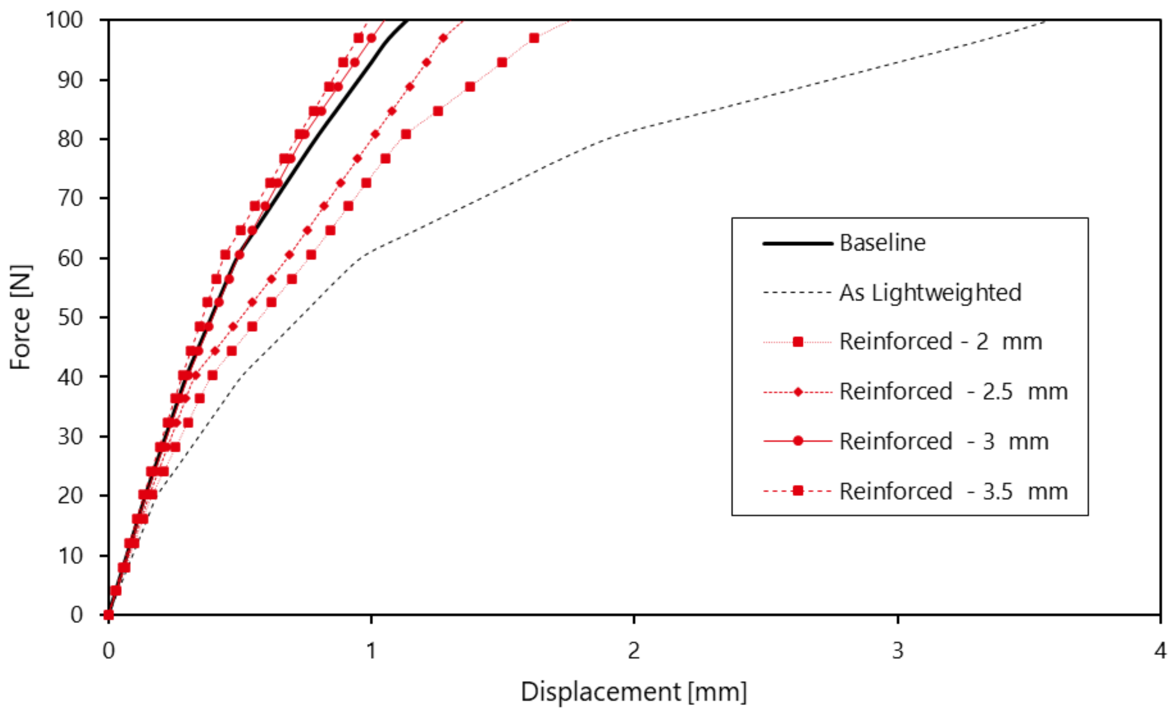

Fig.5: Force displacement profiles for the initial set of structural analysis

3.2 Process Simulation- Results

Fig. 6 presents the von mises stress contour for the front panel (left) and the resultant displacement field in the right. What is apparent, is the increased stresses manifesting in the front outer panel, along the boundaries of both applications. The square shaped increased stress areas towards the bottom of the door are related to the fact that the spotweld elements were assigned different coefficients of thermal expansion in comparison to the elements of the panel.

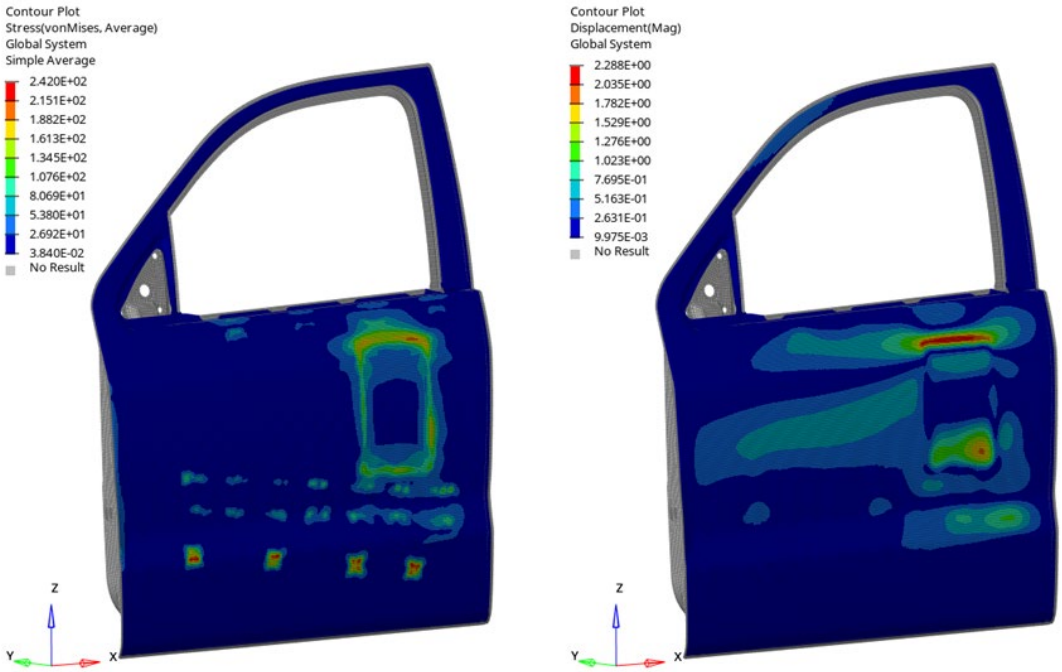

Fig.6: Contour plots of Von-Mises stresses (left) and displacement field (right) for the front outer panel of the door.

3.3 Anti-readthrough application method

Table 3 records the displacement of the indentor for a load of 100N for the cases of baseline, lightweighted, fully reinforced – 3mm thickness and the anti-readthrough optimized case at the same thickness. As it can be seen, only a slight performance drop, associated with increased displacements is exhibited, making such application strategies ideal for avoiding readthrough in very thin outer panels.

Case	Indentor travel at 100N [mm]
Baseline	1.16
As Lightweighted	3.63
Fully reinforced – 3 mm	1.07
Anti-readthrough application 3 mm	1.19

Table 3: Indentor travel at 100 N for different reinforcement cases.

3.4 Process simulation comparison

Fig. 7 compares the plastic strains occurring in the panel after the oven temperature cycle has completed. As it is apparent, the plastic strains (associated with stresses exceeding the yield limit of the panel steel) are significantly reduced in the case of the optimized application method, ensuring that the risk of process induced defects is minimized.

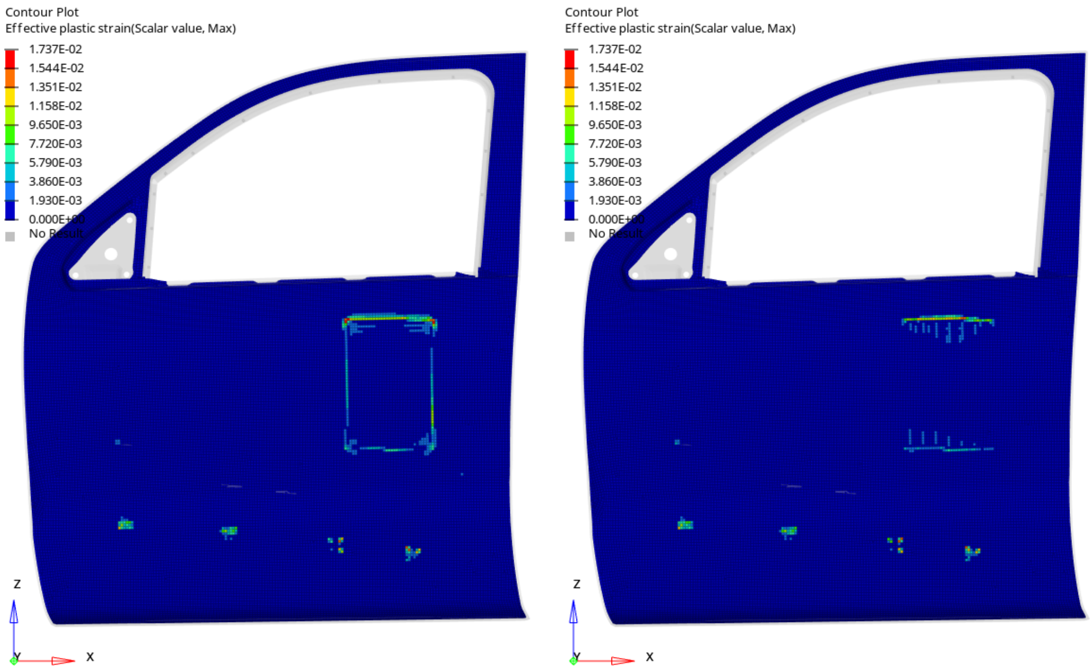

Fig.7: Effective plastic strain of the outer panel for the cases of full application (left) and anti-readthrough application method (right)

3.5 Adhesive joint stress state

One other important aspect of process simulation is studying the adhesive bead stress state. Figure 5 shows the signed von-mises adhesive bead contours. Signed von-mises stress as an LS-PREPOST output contour, assigns a positive or negative sign to the von-mises calculation results so as the user can identify if the dominant loads are compressive or tensile in an element. Fig. 8 depicts the signed von-mises contours for the adhesive bead. One can see that all beads are in compression, a fact that gives confidence that in the case this adhesive had been used for joining the panel and the reinforcement beam, no potential failure would be expected to occur.

Fig.8: Signed Von-Mises stress contour for the antiflutter beads

4 Discussion

Since the implementation of the two Adhesive Curing material models in LS-DYNA, a lot of useful work has been conducted, permitting Henkel Ag &Co KgaA to make informed decisions on product characteristics, to theoretically substantiate what experience, innovation spirit and talent and systematize had already discovered and to improve products based on knowhow and engineering spirit. Having already gained knowhow of using *MAT_277 for CTE mismatch assessment validation we know progress to demonstrate its usefulness towards assessing application methods and understating more about the adhesive joints at an application level.
The techniques demonstrated here are directly applicable to more complex cases that involve understanding the stress state of adhesive joints on whole Body-In-White, especially those that are involving the next generation of crash resistant adhesives.

In the field of 2D reinforcement products but also other adhesive application like the antiflutter case presented here, where the quality of the substrate and its lowest possible permanent deformation, process simulation has proven also very useful, since this permits iterations both in the products properties but also the application method.
Transition of test matrices and techniques to *MAT_307, which is already underway, will permit to further understand better more complex issues like “fingering” damage and address failure of joints.
Nonetheless, even now the engineering knowhow drawn by the use and application of *MAT_277 is quite useful and permits the reduction of time-to-market by reducing the number of iterations needed to ensure that Henkel Ag & Co KgaA’s product development and engineering support functions have state of the art knowhow and capabilities available to support them.

5 Acknowledgements

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6 Summary

This study involves the presentation of a holistic approach towards the structural and process simulation of reinforcements and adhesives joints. Two products are addressed here, namely a sprayable reinforcement, TEROSON RB 5185 and an antiflutter adhesives TEROSON RB 3254. After the lightweighting of a public domain door panel via its thickness reduction, reinforcement measures are applied and the required intervention thickness to return the stiffness required is calculated. Process simulation follows, in order to study the effects of the process to the panels stress state. Then, mitigation

measures based on the application method are introduced and the subsequent process simulation ensues, proving their effectiveness on reducing and mitigating the permanent deformation due to process induced stress state phenomena. Finally, a short discussion ensues on the advantages that are leveraged when studying potential product application not only at performance level, but also at process level.

7 Literature

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