A comparison of Vanderplaats R&D's new STRDOT and DSCDOT optimisers against its BIGDOT optimiser in the application of Formula 1 monocoque design

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Introduction

In recent years the application of VR&D GENESIS in the design optimisation of Formula 1 cars has become increasingly more commonplace, providing significant savings in mass, and improvements in structural performance. With increasing use and understanding comes ever higher demands and expectations on what can be achieved with design optimisation.

In the already complex field of composite laminate optimisation, the ability to consider both stiffness and strength requirements for all stages of the design is a major target for all optimisation tools.

Utilising GENESIS' Composite Topometry optimisation method the concept development of Formula 1 components such as the monocoque and wings has become a reality, providing idealised 'minimum mass' solutions. To date the method has employed VR&D's BIGDOT optimiser, allowing the efficient consideration of extremely large problems in excess of 500,000 design variables. Using this method has allowed multiple stiffness load cases to be considered and, for smaller design problems, strength based loading conditions. However, in large scale problems the consideration of many thousands of strength based design constraints, coupled to a very large number of design variables has resulted in problem formulations that cannot be practically solved using current computer hardware.

Included in the release of GENESIS 10.0 is a new optimiser (STRDOT) which aims to more efficiently consider large scale optimisation problems where stress based constraints are to be considered. By more efficiently considering stress constraints' sensitivities and significantly reducing the required storage of the design sensitivity data, STRDOT is able to reduce the solve time of large scale, stress based problems by factors of up to 100. The first aim of this paper has therefore been to evaluate this new method in the design optimisation of Force India's monocoque design. A Topometry optimisation of the monocoque has been performed, considering 3 stiffness load cases and 3 strength based conditions. Comparison has been made between the performance and results obtained from both BIGDOT and STRDOT.

A second significant challenge in the design optimisation of composites is the efficient consideration of the discrete thickness changes due to the addition and/or removal of individual draped plies. In the case of a complete Formula 1 monocoque the construction typically includes many hundreds of lamina. During the optimisation of an existing laminate construction a study will typically consider changes in ply numbers from 1 to 0 or up to 2. In this case the formulation of the design problem creates normalised

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allowable design variable positions of 0, 0.5 and 1, posing a very difficult problem for a gradient based optimiser. To date BIGDOT has provided significant improvements in laminate design however, as more efficient designs are developed, the benefits of the optimiser over the current design has diminished, therefore putting further demands on what can be achieved through optimisation.

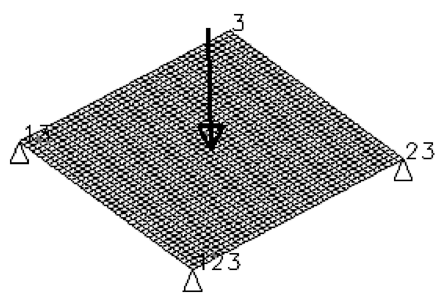
To consider large scale optimisation problems where discrete variable steps are large, VR&D has developed a new optimiser named DSCDOT, which has also been embedded into GENESIS 10.0. To assess the effectiveness of this new optimisation algorithm the detailed laminate design of Force India's monocoque has been optimised to determine which, if any plies, can be removed and where current plies should be duplicated to minimise the design mass. Defined using GRM/OptiAssist the optimisation has linked directly to the monocoques' ply construction, created using Laminate Modeller. An updated layup construction has then been created, allowing the optimised design to be directly passed to the manufacturing.

I.Background of STRDOT and DSCDOT Optimisers

STRDOT[1] is a new and experimental optimizer, which can be used to solve a special subset of structural optimization problems. It is used to resize members of a structure so that certain static stress constraints are satisfied. In GENESIS, this method is typically used in conjunction with the standard methods such as DOT or BIGDOT. STRDOT has been implemented into GENESIS for the efficient consideration of strength based structural problems. During implementation a number of test cases have been performed, in order to validate the process for typical structural problems. Below are two examples of the new STRDOT optimiser:

1. *Example 1: Simply Supported Square Plate under Point Loading*

A square plate comprising of 1,600 elements was constructed and constrained in all three translational degrees of freedom at its four corners. A point load was applied to the centre of the plate and a stress constraint applied to all elements in the model.



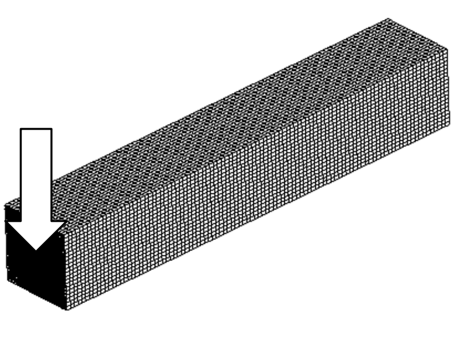
The plate was optimised using both the current BIGDOT optimiser and the new STRDOT optimiser. Table 1, below shows the results of the optimisation, which demonstrate a reduction in both elapsed and CPU times i

of 30 times. The objective is also noted to be very similar, with STRDOT providing a slightly lighter solution.

	Time (seconds)		Ratio (%)		Objective
Optimiser	CPU	ELAPSED	CPU	ELAPSED	
BIGDOT	4599	4617	3.31%	3.34%	0.72
STRDOT	152	154			0.67

Table 1: Summary of Simple Plate Optimisation

2. *Example 2: Composite Box Cantiliver*



A box section cantilever model comprising of 8,000 elements was constructed and fully constrained at one end. A rigid element was created at the free end and a point load applied. The composite layup was defined with 6 uni-directional fibres of orientations 0, 30, -30, 60, -60 0 degrees. A a design problem the thickness of each ply of each element was designed, constraining the allowable failure index in each element to not exceed 1.0.

As with the simple plate the cantilever was optimised using both

BIGDOT and the new STRDOT optimiser. Table 2 overleaf shows the results of both optimisations, which again demonstrate a significant reduction in both the CPU and elapsed times to complete the study. In this second example it can be noted that BIGDOT yielded a notably lower mass than that achieved using STRDOT. This difference may be attributed to the assumptions made to achieve such significant solver time reduction. In the case of the composite cantilever the calculation of failure index is more complicated that the stresses in the simple plate, which may be causing more difficulty for STRDOT during the approximate optimisation phase.

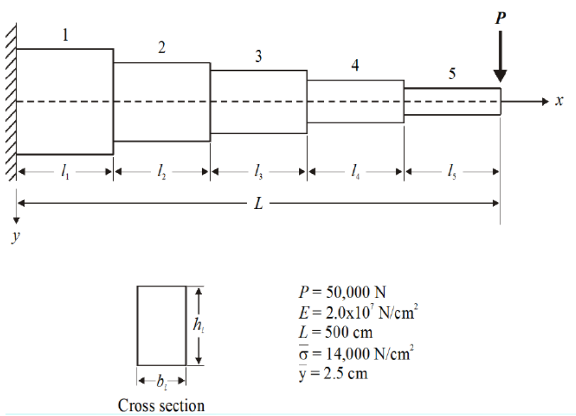
	Time (seconds)		Ratio (%)		Objective
Optimiser	CPU	ELAPSED	CPU	ELAPSED	
BIGDOT	12015	15549	12.73%	13.67%	0.15
STRDOT	1530	2126			0.21

Table 2: Summary of Cantilever Optimisation

The consideration of discrete (incremental stepped) variables is a complex challenge for gradient based optimisers such as those within GENESIS. The consideration of discrete variables is an important part of the optimisaton of composite structures due to material thickness changes being dictated by the adding/removing of distinct plies of a fixed thickness. Whilst GENESIS has supported the optimisation of discrete variables since the introduction of BIGDOT in 1999, the demands on the problem size and complexity have meant that there was an opportunity to improve upon BIGDOT's discrete optimisation capabilities.

As a result of this VR&D have developed DSCDOT, a new discrete optimiser. One of the mains aims in developed DSCDOT was the ability to consider discrete variables where the increment between allowable variables is very large, something that is particularly commonplace in composite optimisation. When considering existing detailed laminate designs the optimiser will often be required to consider the adding to or removal of many hundreds of existing plies. Taking one ply as an example this results in normalised discrete variable positions of 0, 0.5 and 1.0 where 0=0 plies, 0.5=current single ply and 1.0=2 plies.

To benchmark the capabilities of DSCDOT against BIGDOT a cantilever example (shown below) previously used to validate BIGDOT[2] has been used, where the width b and height h of n subsections has been optimised. The objective for the problem is to minimise mass with a stress constraint applied to each section of the cantilever.



Using DSCDOT, the cantilever has been optimised by firstly considering discrete variables increments of 0.1 and then by much larger integer steps. The results of these optimsations are shown in Tables 3 and 4 below, with comparisons made to BIGDOT.

Comparison of DSCDOT to BIGDOT demonstrates a consistent improvement in the objective calculated. More notable is the improvement in objective achieved when the discrete variable increment is large.

PARAMETER	OPTIMUM NDV=10	OPTIMUM NDV=100	OPTIMUM NDV=500	OPTIMUM NDV=5,000
Continuous Optimization				
OBJECTIVE	63,201	61,352	61,297	61,399
MAX G	3.5E-5	4.8E-5	8.2E-5	1.0E-6
BIGDOT Discrete Solution				
OBJECTIVE	64,863	62,517	62,407	62,409
MAX G	-0.008	-0.002	0.0	2.1E-3
DSCDOT Discrete Solution				
OBJECTIVE	64,298	62,024	61,956	62,011
MAX G	4.4E-4	5.3E-3	5.2E-4	5.3E-3
Percent Improvement Over BIGDOT				
	0.9	0.8	0.7	0.6

Table 3: Optimisation results for 0.1 DVAR increments

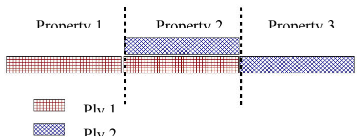
PARAMETER	OPTIMUM NDV=10	OPTIMUM NDV=100	OPTIMUM NDV=500	OPTIMUM NDV=5,000
Continuous Optimization				
OBJECTIVE	63,201	61,352	61,321	61,308
MAX G	3.5E-5	4.8E-5	6.7E-5	2.2E-4
BIGDOT Discrete Solution				
OBJECTIVE	76,700	71,790	71,218	72,175
MAX G	-0.04	0.0	0.0	2.1E-3
DSCDOT Discrete Solution				
OBJECTIVE	72,000	69,180	68,980	69,141
MAX G	-0.002	0.002	0.002	0.002
Percent Improvement Over BIGDOT				
	6.1	3.6	3.1	4.2

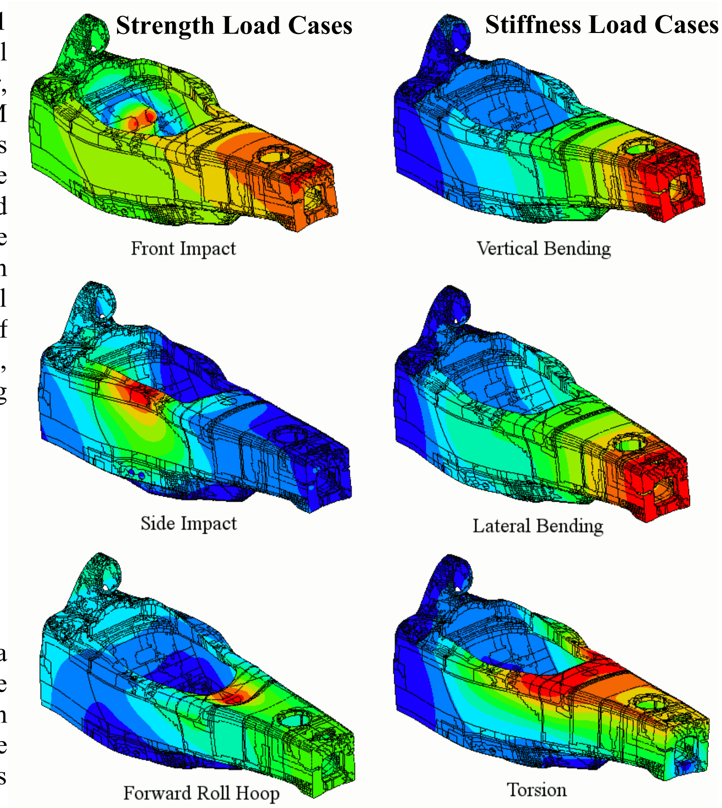
Table 4: Optimisation results for 1.0 DVAR increments

II.Design Optimisation of a Monocoque Design

As a comprehensive test of the current and existing optimisation algorithms incorporated into GENESIS, a study has been undertaken with the Force India Formula 1 Team to optimise the layup of their monocoque design. The study has been broken down into two main approaches; Topometry concept optimisation and a detailed discrete optimisation of the existing layup.

The process of optimising Formula 1 composite layups using GENESIS is well established. A dedicated pre-processor, OptiAssist, has been developed by GRM Consulting Ltd. to link directly to PATRAN's Laminate Modeler and Analglyph Laminate Tools. When considering the design of detailed laminates careful attention must be paid to the assignment of design variables to plies on different property groups which, in the physical component, are the same ply. This facet of composite design, as shown in the figure below, is automatically managed by OptiAssist, ensuring the optimised design can be easily manufactured.





For the design optimisation of the Force India monocoque six load cases were considered, three stiffness based and three strength based. For each loading condition the constraint of the optimisation was to maintain the current layup's stiffness or strength accordingly.

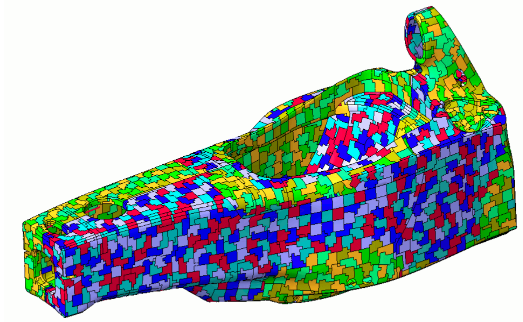
III.Topometry Optimisation of a Monocoque Design

To gain the maximum benefit of optimisation when designing composite laminates the approach of performing a Topometry concept optmisation should be performed. The approach of Topometry is to size optimise each ply of each element, allowing the designer to understand where each type of ply should be placed, therefore defining ply boundaries. Unique to GENESIS are the abilities of considering stress based constraints such as Failure Index and the method known as coarse Topometry. Coarse Topometry allows the user to automatically define groups of elements to be size optimised (in place of each element being sized individually), therefore reducing the number of design variables in the optimisation problem.

To define the Topometry problem constant baseline laminate was defined with the following factors:

- High strength UD plies
- High strength cloth plies
- High stiffness UD plies
- High stiffness cloth plies
- Core material
- Ply angles of 0º, +45º & -45º

The thickness of each ply was designed, including the core. The objective of the optimisation was defined to minimise mass, whilst stiffness and stress constraints were applied for the above load cases. In order to reduce the optimsation problem size, therefore reducing solve time, a Topometry Coarsening factor of 25 was used. The resulting element groupings are shown in the figure overleaf.



With the defined parameters the problem definition resulted in a very large design problem as detailed in Table 5, below.

Design Variables	32,814
Potential Constraints	21,533,886

Table 5: Topometry Optimisation Summary

The Topometry optimisation of the monoque was performed using both STRDOT and BIGDOT for comparison. Due to the problem size the initial optimisation using BIGBOT failed to solve due to insufficient storage for the design sensitivities. Review of the optimisation problem revealed that in excess of 70GBytes of storage would be required, more than was available. A number of trial studies were therefore performed which revealed that the design problem could be successfully optimised using BIGDOT by tuning the constraint screening and move limit parameters to reduce the required storage. The settings finally used should be applicable to most large, stress based optimisation problems, reducing the storage requirements for sensitivity calculations to approximately 10Gbytes. Comparison of the results obtained by BIGDOT and STRDOT are shown in Table 6 below.

	Time (seconds)		Ratio (%)		Objective
Optimiser	CPU	ELAPSED	CPU	ELAPSED	
BIGDOT*	34712	29465	27.58%	22.64%	0.74
STRDOT	9573	6672			3.73

Table 6: Topometry Optimisation Results Summary

Comparison of the results between the two optimisers demonstrates, again, the significant efficiency gains in using STRDOT to solve stress based optimisation problems. In the case of the monocoque, however, it can be noted that, whilst all constraints were satisfied, the objective achieved was significantly higher than that obtained by BIGDOT. It is believed that the increased objective can be attributed to two factors, the approximation of the failure index calculations and the consideration of multiple stress based load cases.

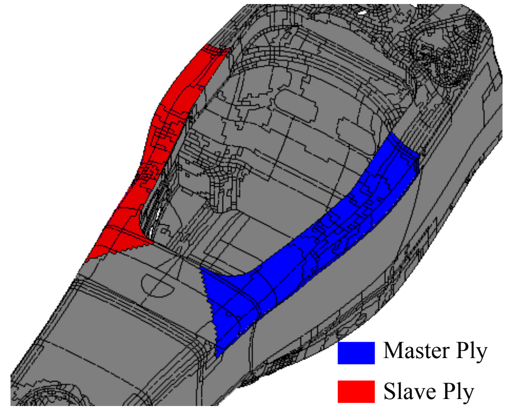
Two conclusions can therefore be drawn from the optimisation of the monocoque. Firstly, through the tuning of certain optimisation parameters, utilisation of the BIGDOT optimiser has yielded a significant mass saving of 28% on the current laminate design. Whilst other factors may prohibit this total mass reduction from being achieved, by uniquely considering both stiffness and strength load cases GENESIS design optimisation offers engineers the opportunity to achieve minimum mass solutions in extremely short timescales. Secondly, whilst the STRDOT optimiser has been demonstrated to provide significant time and storage savings on PSHELL stress type problems whilst achieving similar objectiv values, for the consideration of large scale, composite problems, BIGDOT provides significant benefits when optimisation parameters are tuned.

IV.Detailed Discrete Optimisation of a Monocoque Design

As the second stage in a complete optimisation of a composite laminate the number of plies for each placed lamina should be designed. Typically, the ply boundary will be previously defined based upon the Topometry results, however, as this study is aimed at considering the new optimisers within GENESIS, the current laminate to the Force India monocoque was used as a starting point.

As discussed previously, the design of detailed laminates such as a Formula 1 monocoque is defined using Laminate Modeller tools such as those in MSC/PATRAN or Anaglyph Laminate Tools. When optimising such composite laminates the problem must be defined such that design variables are assigned to layers on multiple composite properties, ensuring that a manufacturable design results from the optimisation. Using GRM/OptiAssist this has been done for the monocoque, designing a total of 609 plies, ignoring plies that cannot be designed. Again utilising the design set-up facilities of OptiAssist symmetry for 120 pairs of plies has been defined as shown in the figure overleaf.

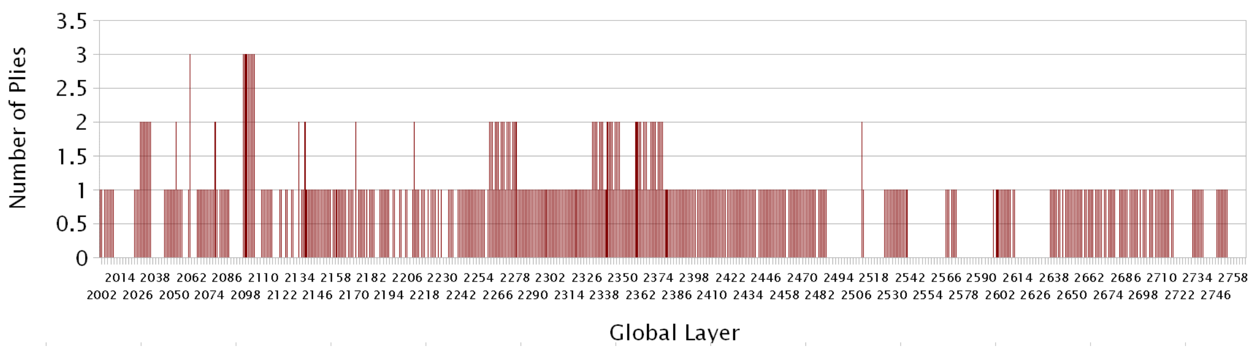
With the optimisation problem defined a sizing optimisation of the detailed laminate was performed using both BIGDOT and the new discrete optmiser DSCDOT. Table 7, below, shows the results obtained from both optimisers and demonstrates that the new optimiser, DSCDOT, provides a significant improvement in compared to both BIGDOT and the current laminate with a mass reduction on the current layup of 16%.



Optimiser	Normalised Objective
BIGDOT	1.16
DSCDOT	0.84*

Table 7: Detailed Sizing Results Summary

When post-processing the results of a detailed sizing optimisation, interpretation of the results can often be an extremely complicated process. GRM/OptiAssist therefore offers a number of methods for the engineer to review the results. Firstly the layup file used to define the laminate construction can be interactively updated, ready for opening by Laminate Modeller or Laminate Tools. Secondly the number of plies for each global layer can be viewed using VR&D Design Studio to understand visually where existing plies should be duplicated or removed. Finally a summary of each global layer is created which can be easily read into any spreadsheet software package. The figure below shows the results of the optimisation of the Force India monoque using this latter option.



V.Conclusion

Utilising VR&D GENESIS, design optimisation has become integral part of the Formula 1 design process with many teams taking advantage of GENESIS' unique optimisation capabilities for composite laminate design. This increased use has, however, put high demands on the integration of optimisation into existing composite development processes. The increased use has also significantly increased the expectation of what can be achieved by optimisers for both solve time and objective result.

To address this demand two new optimisers have been developed by VR&D to add to the existing standard in design optimisation, BIGDOT. In this paper, these optimisers have been tested on one of the most complicated structural problems, which is the design optimisation of a formula 1 monoque.

Whilst STRDOT showed significant speed improvements, the initial release does not provide close enough answers to the well established BIGDOT for large composite problems. That said, the test problems have shown that significant solve time savings can be achieved for non-composite problems, whilst achieving similar objectives to those obtained by BIGDOT. Future releases of STRDOT will no doubt improve to better support composite type problems.

The introduction of DSCDOT shows immediate benefits over the existing discrete optimiser in BIGDOT. It is therefore assumed t hat DSCDOT will supersede BIGDOT discrete solution in future releases of VR&D GENESIS.

References

[1]Vanderplaats Research & Development Inc, "GENESIS Design Manual - Version 10.0," 2008.

[2]Vanderplaats, G. N., "Very large Scale Optimization," *Symposium of Multidisciplinary Analysis and Optimization*, AIAA, Long Beach, 2000.