INVESTIGATION OF NOVEL BAGASSE FIBRE HYBRID CRASH BARRIERS USING NUMERICAL SIMULATION

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Keywords: bagasse, crash barrier, FE simulation, LS-Dyna, sugarcane

Abstract
Sugarcane bagasse is an agricultural by-product of the sugar production process. Australia is the eighth largest producer of sugar in the world producing over 5 million tonnes of sugar per year resulting in 11 million tonnes of bagasse. The development of industrial products from locally sourced bagasse provides a prospective solution for the utilization of this abundant resource. Natural fibres such as bagasse are a lightweight material due to their low cellulose content and are suitable for energy absorption applications, where high strength and stiffness are not critical. This paper investigates the viability of bagasse as an energy absorption material in a hybrid crash barrier. Numerical crash simulations were performed using the commercial explicit finite element software, LS-DYNA. The frontal impact of a Chevrolet C-1500 pick-up truck on rigid concrete barriers and different configurations of the proposed barriers were modelled in LS-Dyna. The crash modelling presented in the paper proves the effectiveness of flexible crash barriers in improving the chance of occupants' survivability and show the capability of natural fibres such as bagasse in producing cost-effective and sustainable composite products.

1. Introduction

The need to develop new technologies focused on the reduction of environmental impact of industrial processes has sparked interest in replacement of artificial fibre reinforcements such as glass, aramid and carbon with renewable resources such as natural fibre reinforced composite materials. The abundance of natural fibres and ease of manufacturing have allowed researchers to try locally available inexpensive fibres and to study their viability as reinforcements in polymer composites. Natural fibre composites have many advantages in addition to being derived from a renewable resource, namely; they are biodegradable, in most cases are CO_2 neutral and apply low energy production processes. They also possess cost and weight saving potential due to their low raw material price and low density. During the last few years, research on natural fibres derived from hemp, sisal, jute, cotton, flax and broom have been undertaken to replace the conventional synthetic fibre composites [1]. Despite the interest and environmental appeal of natural fibres, their use has been limited to non-load bearing applications due to their lower strength and stiffness compared with synthetic fibre reinforced polymer composite. The stiffness and strength shortcomings of these bio-composites can be overcome by physical and chemical treatments, structural configurations and better arrangement of fibres within the matrix to provide specific mechanical properties that are analogous to that of traditional fibres.

Excerpt from ISBN 978-3-00-053387-7

Natural plant fibres are categorised into bast, leaf or seed fibres. Bast fibres consist of a woody core surrounded by a stem [2]. The stem contains individual fibre cells or filaments which are made up of cellulose and hemicellulose and is bound together by pectin or lignin which acts as a natural matrix system. Common bast fibres include hemp, flax, ramie, jute, kenaf and bagasse. Bagasse is an underutilised, renewable agricultural by-product of the sugar production process derived from the crushing of sugarcane. Australia is the eighth largest producer of sugar in the world producing over 5 million tonnes of sugar per year which results in 11 million tonnes of bagasse fibre waste. Presently, the bagasse waste is burned by the sugar mills as an additional source of energy, sold as mulch or sent to landfills [3]. The development of high quality industrial products from bagasse waste provides a prospective solution for bagasse utilization. The associated costs of extraction, chemical modifications and/or other pre-treatments of bagasse to transform the fibre waste to ready-to-be used materials are low [4]. Several researchers have succeeded in utilizing sugarcane bagasse waste as reinforcement in polymeric matrices to produce low cost composites [5-9]. Most of the research has focussed on bagasse fibre reinforced thermoplastic resins such as poly vinyl chloride and polypropylene [5-8]. The fabrication of bagasse composites in thermosetting resin does not involve high pressures and does not require high temperatures and therefore the problems associated with the degradation of the reinforcement during manufacture are less significant than for composites with thermoplastic matrices [9]. Bagasse is known to have sufficient thermal and sound absorption properties and the Colonial Sugar Refining Co. Ltd. (CSR) made a low density insulating soft-board out of bagasse fibre known as Cane-ite for use as a ceiling lining [10]. Loh et al. [11] summarised the various applications of bagasse fibres including producing tableware packaging mixed with gelatin, starch and agar and in manufacturing of concrete and ash block.

Bagasse has generated a considerable amount of interest in the field of impact resistance and energy absorption. Crash barriers are designed to absorb as much energy as they can, hence transmitting as little energy back to the car and reducing the risk to injury to passengers. According to Gupta and Kelkar [12], a well-designed barrier should be capable of absorbing the kinetic energy of a car in a controlled manner, with a low rebound velocity. Barriers tend to replicate a train buffer system, behaving like spring or dampers [13]. They absorb energy by deflection, dissipating some of it via the damper part, and storing and releasing the remainder, via the spring. Some barriers also slow the car by momentum transfer: the car collects heavy parts of the barrier, and by the principle of conservation of momentum, its speed is reduced proportional to the increase in the mass of the car plus the barrier.

There are many different types of crash barriers associated with specific applications but the most common forms of crash barriers are the guardrails and median barriers, which can be classified into three categories: weak post systems (also known as flexible energy absorbing barrier), strong post systems and rigid concrete barriers [14]. In reality, most barriers combine material failure, momentum transfer, spring and damper in a complex interaction [15]. Pure material failure (crushable) barriers such as Armco and foam blocks, have not found the favour one might expect as they are one-shot systems. Concrete barriers are the most widely used barriers as they withstands impacts without much damage, and so does not require refurbishment or replacement. However, it has been proven in many tests that a flexible energy absorbing barrier can perform better than a rigid barrier under explosive or crash conditions [12]. Rigid barriers will fail under relatively small impact velocities, while energy absorbing barriers will be able to survive much higher velocities. The full scale crash testing of different barriers with numerous variables such as velocities and impact angles would be prohibitively expensive even if damaged or repaired cars were used. Finite element modelling has been recommended as an alternative to crash testing. The developed model must be able to accurately simulate the dynamics of the car and the energy absorbing phenomenon in the barrier. Tryland [16] developed a computationally efficient approach to model the crash performance of deformable barriers based on aluminium honeycomb. Marzougui et al. [17] and Abdellatif and Marzougui et al. [18] have developed and validated several FE models for the full-scale crash simulations with vehicle models created in LS-Dyna. Mackerle [19] presented a detailed bibliography of finite element simulations of

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crash and impact-induced injuries not limited to automotive crashworthiness. Liao et al. [20] used full-scale vehicle simulation that undergoes both the full frontal and 40% offset-frontal crashes to demonstrate the capability and potential of this procedure in the solving and optimization of crashworthiness design of vehicles.

2. Development of the Crash model

2.1. Finite element model of the vehicle

A detailed finite element model of a 1994 Chevrolet C-1500 pick-up truck, shown in Figure 1, was developed at the National Crash Analysis Centre (NCAC) [21]. According to Marzougui et al. [17], the C2500 pickup truck has been the primary test vehicle in many roadside hardware evaluation and certification crash tests.This model was developed by NCAC of The George Washington University under a contract with the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA) of the US DOT. This FE model has been extensively used in many previous roadside hardware simulations and verified by European New Car Assessment Programme (NCAP). This vehicle model was selected to be used in the crash simulations for all the analysis in this report.

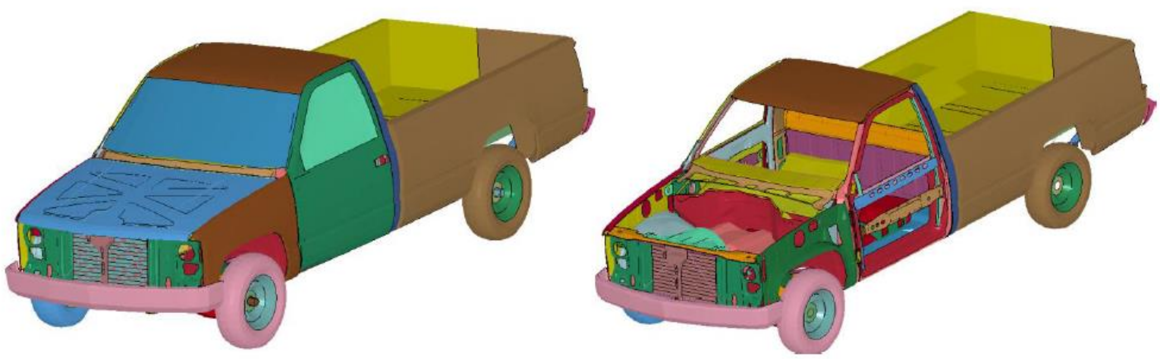

Figure 1. Isometric view of C1500 Pick-up Truck model (with and without hood)

It has been reported that current seat and head protection padding allows drivers to consistently survive side and rear impact that generate of the order of 150g without injury. Wright [15] concluded that the critical impact direction is head-on and about 30 degrees either side and that a well-restrained driver should be uninjured in a frontal impact of 30g. Thus it was decided that a frontal test is the critical case for barrier design. Marzougui et al. [17] modelled the front components of the vehicle in fine detail in order to obtain reasonable agreement with crash-tests concerning overall motion and deformation profiles in the high deformation regions.

Figure 2 shows the two designs of the hybrid crash barrier designed with a bagasse composite block sandwiched in the middle between 6mm GFRP layer at the front and a 250mm thick concrete block at the back. In the first hybrid design, there is no gap between the bagasse layer and the concrete layer. In the second design, an offset of 250 mm is introduced between the bagasse and the concrete to allow the composite layer to deform and absorb large amount of energy. The height of the barriers in both designs are 1 m and the span of the barriers are 4 m.

The GFRP layer was modelled as a 12ply (0-90) layup for a 6 mm thick layer using Belytschko-Tsay shell elements. The composite layer is modelled with 10000 elements. LS-DYNA consists of an extensive range of material models used to define various metals and composites. The material model chosen to define the GFRP facesheet was Laminated Composite Fabric model available in the library as MAT58. This composite material model is ideally suited for thin shell elements of orthotropic

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materials. The failure criterion works by deleting the damaged elements in the composite layers of the model, hence enabling the vehicle to penetrate the material as expected in a physical test. The input data for this material model was obtained from previous UNSW research project and a modulus of the GFRP layer was 16.28 GPa with a tensile strength of 361 MPa and compressive strength of 300 MPa was used in the model.

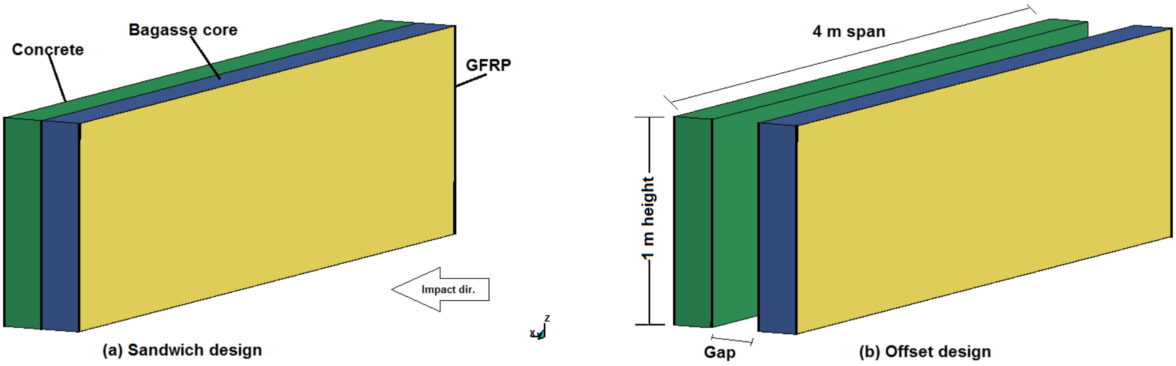

Figure 2. Hybrid crash barrier designs (a) Sandwich model and (b) Offset design

The bagasse layer is modelled with 50000 hexahedral brick elements. The material properties of bagasse used in these simulations were obtained from experimental results produced by uniaxial compression test of a bagasse sample cylinder with different volume fractions (60, 70 and 80%). The bagasse composite is a lightweight foam like material with a density of 45 kg/m^3 and a modulus of 300 MPa [22]. The yield stress, densification stress and Young's modulus were obtained from the compressive stress-strain curve which defined the material behaviour of varying fibre volume fraction samples as shown in Figure 3. The non-linear material model chosen to define the bagasse composite was a PIECEWISE_LINEAR_PLASTICITY model (MAT24). This material model is often used to define a Multi-linear Isotropic Hardening material type and enables the specification of the experimental input and failure strain curve to accurately define the material behaviour.

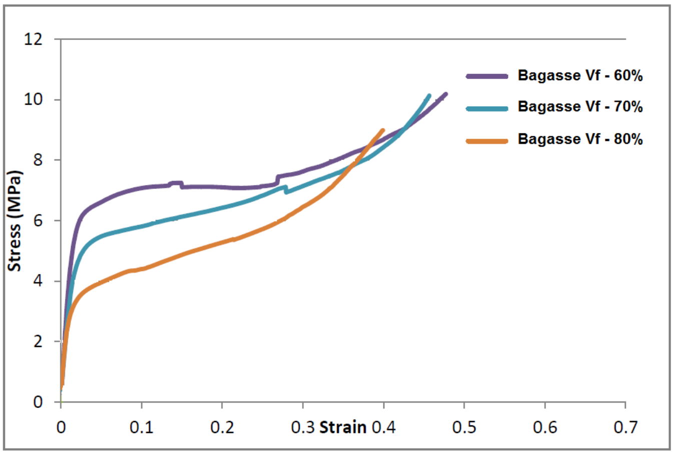

Figure 3. Uniaxial compression test results for bagasse fibre composite with different volume fractions

Lastly, the material model chosen to define the concrete barrier, which is also modelled with hexahedral elements, was RIGID (MAT20). This material type provides a convenient way of turning one or more parts into a rigid body. The rigid material model ensures that the concrete block does not deform during the vehicle impact, and it is also highly preferred in many crash simulations. The contact definition used between the GFRP and bagasse as well as between bagasse and concrete is AUTOMATIC_SURFACE_TO_SURFACE. For this contact definition, the slave nodes are constrained to move with the master surface.

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2.2. Results of the crash simulation

The energy balance analysis is an important step in the validation of the FE model and verifies that the conservation of energy condition is satisfied. This can be accomplished by comparing the internal energy and kinetic energy in the model. Figure 4 below shows the energy balance for a typical crash simulation into a sandwich barrier design for a case of initial velocity 40 km/h. The simulation was solved for a total duration of 0.15 seconds (150 ms). It can be observed that the total energy remained approximately constant throughout crash, and the rise in internal energy and the decay in kinetic energy are smooth. This confirms that there is very little inter-penetration among the contacted segments, therefore increasing the accuracy of the results. The final internal energy in the model does not reach the initial kinetic energy and a difference of approximately 50 kJ is recorded. Some of the energy is Hourglass energy from the excessive distortion of elements and some of the energy is lost as sliding energy in the contact areas. The reminder of the difference in the energy is basically the rebound kinetic energy of the vehicle after the crash (i.e. the vehicle impacts the crash barrier and bounces back with a small residual velocity).

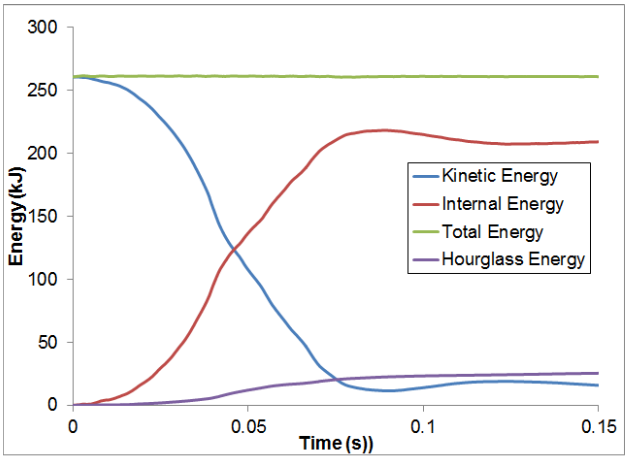

Figure 4. Energy balance of the crash simulation at 56 km/h initial velocity.

Figure 5 shows the comparison of the contact force history between the pickup truck and the crash barrier for the two designs of the hybrid barrier. It can be seen that the sandwich barrier has higher contact force due to the rigid boundary condition of the bagasse layer which does not allow large deformation. On the other hand, the contact force peak is reduced by more than 10% for the offset hybrid barrier. This is because the GFRP and bagasse layer has large plastic deformation which is evident from the displacement. In addition to reducing the peak force value, it is shifted rightward, from 400 mm to 580 mm.

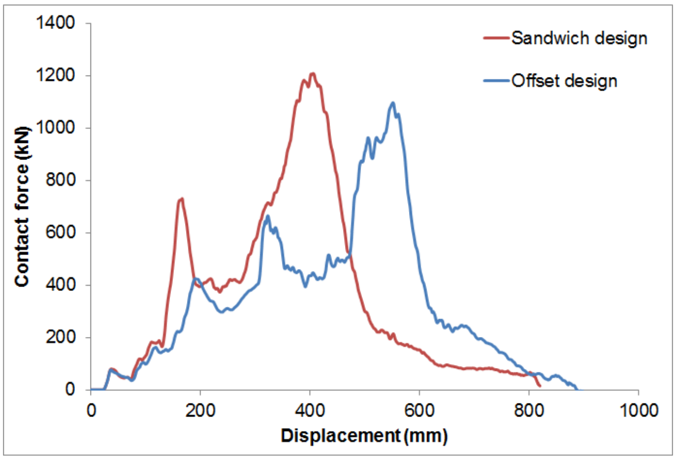

Figure 5. Comparison of the force history of the sandwich design and offset design

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The progression of the vehicle impact on the offset crash barrier is depicted in Figure 6. The GFRP and bagasse block are constrained at the sides and the rigid concrete block at the back is constrained at the bottom. This design replicates simply placing the GFRP and bagasse block at a pre-determined offset distance away from the concrete block with no installation required. When the car impacts into the barrier, this energy is transferred along the length of the bagasse block from the contact surface in the center, dissipating towards the left and right evenly until it reaches the end (constrained surfaces), resulting in a wave-like effect. In addition to localized deformation at the point of impact, there is global bending of the bagasse composite till the rear surface comes in contact with the concrete layer. In the force – displacement curve, this point when the bagasse layer comes into contact with the concrete corresponds to the 610 kN peak. This global deformation acts as a spring and provides a cushioning effect to the crash which allows gradual deceleration of the vehicle. At the end of the impact, the composite layer has recovered some of the deformation, as can be seen in the top view. The deformation of the flexible barrier absorbs the impact energy more efficiently.

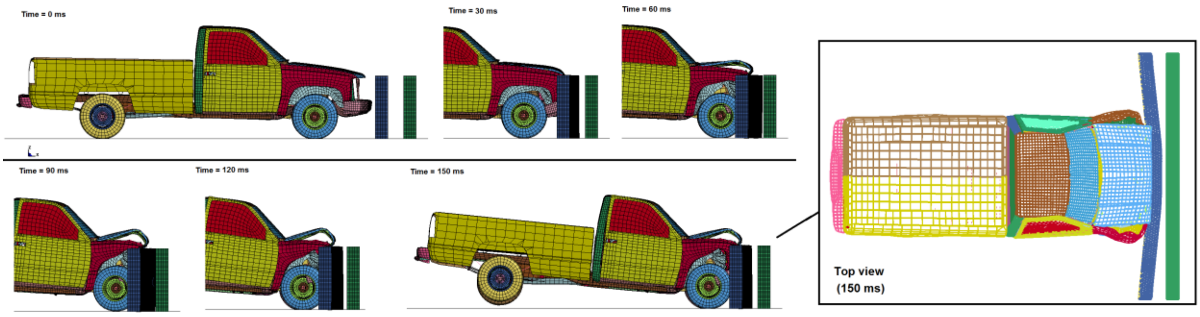

Figure 6. Progression of impact in the case of offset hybrid crash barrier (Design 2) for V= 56 km/h

Figure 7 shows the comparison of the simulation results for the proposed hybrid barrier (Design 2) and the rigid wall crash simulations of NCAC. The kinetic energy vs. time curve shows that the deformable barrier allows the gradual deceleration of the vehicle by absorbing the energy in the deformation of the bagasse layer and therefore reduces the risk of injury. It can also be seen that the deformable barrier with bagasse fibre barrier offset at a distance from the rigid concrete barrier reduces the peak deceleration measured by accelerometer placed in the right seat of the vehicle from 50 g to 40 g. This is a sizeable reduction of 20% in the acceleration pulse experienced by the occupant. This hybrid design is more likely to reduce severe injuries and fatalities. It was also observed in other simulations with varying lengths of the barriers and offset distances, that is was possible to optimize the deceleration behavior of the vehicle. For instance, with barriers of length 20 m, the resultant acceleration was 42 g but the kinetic energy response was different to the design shown here.

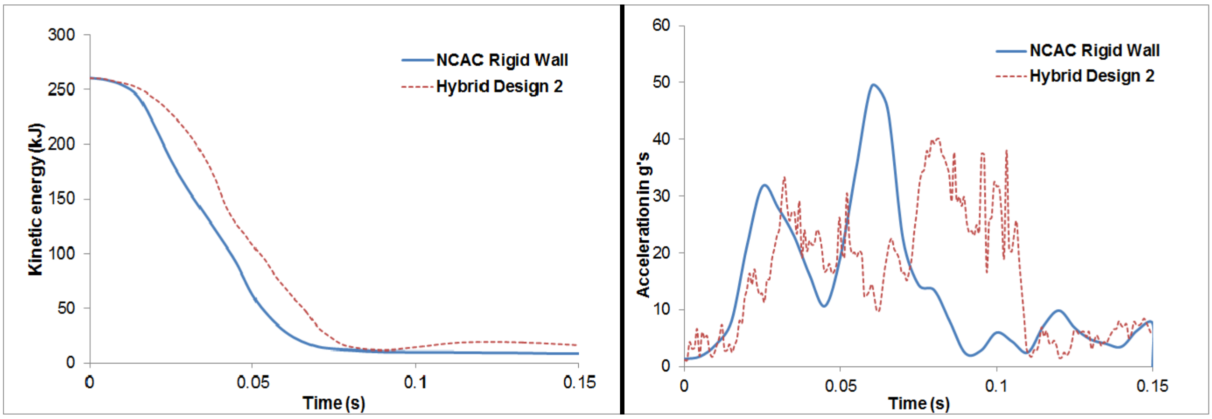

Figure 7. Comparison of kinetic energy and resultant acceleration response for V= 56 km/h

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3. Conclusions

This paper presented the viability of designing hybrid crash barriers with the natural fibres derived from sugarcane bagasse. Full-scale crash simulation was conducted using FE software LS-Dyna on two designs of hybrid composites. Simulation results were compared with the results gathered from NCAC for rigid wall impact and verified to be accurate. Using bagasse as an energy absorption material in a crash barrier has been proven to be a viable solution, even though that is largely dependent on the design of the crash barrier as seen comparing the sandwich block design to the concrete wall offset designs. Preliminary FEM results proved the importance of having a GFRP facesheet instead of using a bagasse composite core alone.The concrete wall offset (Design 2) is found to be the most ideal solution, with a bagasse core of 250mm thickness and 6mm GFRP facesheet, as it results in the most gradual deceleration and lowest resultant peak force. Comparing the average seat cross member accelerations in the simulations to that of NCAP and FMVSS 208 requirements have shown that the design of crash barriers used is this report is acceptable and has satisfy those essential requirements. This report has concluded that with the correct design, a bagasse core crash barrier is a viable solution, lowering the crash pulse and deceleration (G's) upon an impact, and therefore increasing the chances of occupants' survivability in a crash scenario. Recommendations for future work is to include a dummy model with restraint systems, like the seatbelts, airbags and energy absorbing steering column in the vehicle to accurately observe and analyse the behaviour of occupants in crash scenarios in order to accurately determine their survivability.

References

[1] A.K. Bledzki, J. Gassan, Composites reinforced with cellulose based fibres. Progress in Polymer Science. 1999. 24.
[2] M.S. Salit, Tropical Natural Fibre Composites : Properties, manfucature and applications, Springer Publications, ISBN 978-981-287-154-1
[3] William Thompson, Manufacture and characterisation of bagasse fibre composites, Undergraduate Thesis, UNSW, 2012
[4] Y.R. Loh, D. Sujan, M.E. Rahman, C.A. Das, Sugarcane bagasse—The future composite material: A literature review. Resources, Conservation and Recycling, Volume 75, June 2013, Pages 14-22
[5] Riza Wirawan, S.M. Sapuan, Robiah Yunus and Khalina Abdan, Properties of sugarcane bagasse/poly(vinyl chloride) composites after various treatments. Journal of Composite Materials (2010), 45(16) 1667–1674
[6] Yong Cao , Koichi Goda & Shinichi Shibata, Development and mechanical properties of bagasse fiber reinforced composites, Advanced Composite Materials, (2007)16:4, 283-298
[7] Youssef, H. A., Ismail, M. R., Ali, M. A. M., Zahran, A. H., "Effect of the Various Coupling Agents on the Mechanical and Physical properties of Thermoplastic-Bagasse Fibre Composites," National Centre of Radiation Research and Technology, Cairo, Egypt, 2008.
[8] Youssef, H. A., Ismail, M. R., Ali, M. A. M., Zahran, A. H., "Studies on Sugarcane Bagasse Fibre – Thermoplastic Composites," Journal of Elastomers and Plastics, Vol. 24, pp. 245-262, 2009.
[9] J. M. F. Paiva and E. Frollini, Sugarcane bagasse reinforced phenolic and lignophenolic composites, Journal of Applied Polymer Science, 2002 (83:4), pages 880–888
[10] "Fibreboards," Technology in Australia 1788-1988, Australian Science and Technology Heritage Centre, University of Melbourne, Parkville Victoria, Chap. 4.
[11] D. Verma, P.C. Gope, M.K. Maheshwari, R.K. Sharma, Bagasse Fiber Composites-A Review, J. Mater. Environ. Sci. 3 (6) (2012) 1079-1092
[12] Dr. Gupta, R. and Dr. Kelkar, A., Nonlinear Crash Dynamics Simulation of Novel Airbag Based Next Generation Energy Absorbing Barrier, Department of Mechanical Engineering, North Carolina A & T State University, 2010.

Excerpt from ISBN 978-3-00-053387-7

[13] Jacob, G., Energy Absorption in Polymer Composite Materials for Automotive Crashworthiness, University of Tennessee, USA.

[14] R.P. Bligh, S.P. Miaou, D. Lord, and S. Cooner, Median Barrier Guidelines for Texas (FHWA/TX-06/0-4254-1), Texas Transportation Institute, Texas A&M University, College Station, TX, 2006

[15] Wright, P., Technical Barriers, Grand Prix Features – Inside F1, 2001 http://www.grandprix.com/ft/ftpw016.html

[16] T Tryland, Alternate models for the offset and side impact deformable barriers, 9th International LS-Dyna Users conference, Michigan, 2006

[17] D Marzougui , M Zink , A Zaouk , C D Kan & N Bedewi, Development and validation of a vehicle suspension finite element model for use in crash simulations, International Journal of Crashworthiness, 9:6, 565-576, 2004

[18] Abdullatif K. Zaouk and Dhafer Marzougui, Development and validation of a US side impact moveable deformable barrier FE model, European LS-Dyna Users conference, 2001

[19] Jaroslav Mackerle, Finite Element Crash Simulations and Impact-Induced Injuries: An Addendum. A Bibliography (1998-2002), The Shock and Vibration Digest 2003; 35; 273

[20] Xingtao Liao, Qing Li, Xujing Yang, Weigang Zhang, Wei Li, Multiobjective optimization for crash safety design of vehicles using stepwise regression model, Structural and Multidisciplinary Optimization, 35(6): 561-569, 2007

[21] Finite Element Model Archive, National Crash Analysis Centre, http://www.ncac.gwu.edu/vml/models.html

[22] KR Ramakrishnan, W Thompson, K Shankar, MA Ashraf, "Impact behaviour of natural fibre reinforced composites based on bagasse fibres", International conference on Mechanics of Composites – Stony Brook, 2014

Excerpt from ISBN 978-3-00-053387-7