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Non-direct similitude technique applied to the dynamic axial impact of bonded crush tubes

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ABSTRACT

The use of lightweight materials in vehicle structures requires appropriate joining techniques, among them adhesive bonding. Testing full-scale structures such as vehicle crush tubes can be prohibitive in terms of cost and appropriate facilities may not be available, so it is often desirable to test sub-size structures. To address this need, the suitability of scaling to accurately describe the behavior of bonded crush tube structures during axial impact scenarios was investigated. A numerical simulation was validated using literature sources and experimental testing, and then used to investigate scaling. The predictions for structures constructed out of a single material, in terms of stress distributions and deformations were in good agreement between the numerical simulations of the model (experiment modified in size by a scale factor) and the prototype tubes (actual size experiment). When considering bonded structures with the possibility for joint separation, the Non-Direct Similitude technique was applied to scale the structure and the results showed a small departure between the predictions of the model and the prototype. For bonded crush tubes, where the presence of a second material in the form of an adhesive layer was small, the scaling method provides acceptable results. The limitations of the scaling technique were discussed.

1. Introduction

An essential element of increased fuel efficiency in transportation systems is the use of lightweight structures [1]. Lighter structures can be achieved through the use of thin sections, optimized materials and/or novel geometries, but are often limited by current joining techniques. For example, spot-welding operations require minimum thicknesses and compatible materials, which may hinder weight savings. Also, novel geometries such as tapered crush tubes [2] may not be achievable with conventional manufacturing techniques. These challenges have encouraged the use of high strength and high tenacity adhesives.

Several authors (Table 1) have investigated different types of structures, such as closed sections and adhesively bonded structures made from channels and hat sections, under quasi-static loading and dynamic impact conditions; however, the testing of these structures in the expected range of strain rates for automotive crash scenarios is challenging in terms of cost and equipment requirements. The use of actual representative structures (1:1 dimension ratio) emulating a recognized standard (e.g. NCAP), requires equipment that delivers high energies (e.g. 800 kg at 17.8 m/s), and extensive testing programs (i.e. many repeat tests) may not be economically feasible when statistical confidence is required. To overcome these challenges, scaled axial crush tube structures were explored.

The problem of structure scaling for dynamic impact events is widely acknowledged and has hindered the use of sub-size samples to understand many different phenomena in engineering structures under dynamic loads [9]. At present, strain rate and inertia effects have been posed as the main limitation for traditional or non-corrected (NC) scaling laws under impact scenarios, but Oshiro and Alves have overcome these difficulties by adapting a technique called Non-Direct Similitude (NDS) [10–12], in which strain rate effects were addressed by changing the impact velocity. By including the strain rate effect, complete similarity or agreement between the structure and its sub-size sample, can be reproduced. In more recent work, the same authors [13] have successfully explored scaling structures using geometrically distorted models. It should be noted that standard (NC) scaling will, in some cases, produce results similar to NDS. However, this is case specific and for the current study our focus was on the application of NDS since this technique accounts for material strain rate effects.

In brief, NDS considers strain rate effects by finding the necessary initial impact velocity such that the experiment of interest is

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Table 1
Axial crush tubes in dynamic impact, literature survey.

Author	Type of structure & material	Impact conditions	Avg. force [kN]
Abramowicz & jones [1]	Square steel tubes	Drop hammer 75 kg up to 10.4 m/s	
	1.5 in sq. tubes various lengths (100–200 mm)		30
	2.0 in sq. tubes various lengths (100–200 mm)		50
Langseth et all [2]	Square aluminum tubes	Pneumatic accelerator 55 kg up to 19.8 m/s	
	80 mm sq. x 310 mm		20 to 70
Schneider & Jones [3]	Steel spot welded top hats and laser weld Close squares	Drop hammer Up to 211 kg up to 16 m/s	
	60 mm sq. × 350 mm		25
	Top hat 60 mm × 15 mm flange × 300 mm		30 to 40
Tarigoupla et all [4]	High strength steel sections	Kicking machine 600 kg up to 15 m/s	
	60 mm sq. × 310 mm		40
	60 mm × 25 mm flange × 310 mm		50
Peroni et all [5]	Different bonded box configurations	Drop tower 60 kg up to 13 m/s	
Peroni et all [6]	Bonded steel sections and welded close Sections	Drop tower Up to 200 kg up to 13 m/s	
	40 mm sq. tubes out of channels × 300 mm		14
	Top hat 40 mm w 15 mm flange × 300 mm		15
Belingardi [7]	Low carbon steel	Drop tower 60 kg up to 9 m/s	
	Top hat 60 mm × 15 mm flange × 300 mm		10
	2 hats: 60 mm section × 300 mm		18
	2 U channels: 60 mm section × 300 mm		10
Avalle et all [8]	Bi material joining: Steel & aluminum	Drop tower 60 kg up to 13 m/s	
	Double hat: 40 mm × 15 mm flange × 300 mm		18
	Double C: 40 mm × 300 mm		10

properly scaled. A properly scaled experiment means that not only significant quantities, such as force, are accurately predicted through the use of non-dimensional numbers but also that there is agreement in the physical behavior between the subject and the scaled counterpart (e.g. same deformation patterns). The scale factor is generally selected so that the event can be replicated more conveniently. Possessing the ability to replicate events at more convenient scales (i.e. smaller) is of great advantage for many industries; aeronautical, marine transportation, pressure vessels, civil construction among others; where testing an application at full size may be cost prohibitive. In the current study, we are investigating sub-sized adhesively bonded automotive structures that can be tested on available lab equipment; whereas full-scale structures would require a large crash sled and significantly more material and time to construct, limiting the number of repeats and iterations that could be investigated.

Reproducing structural behavior using a smaller scale experiments is termed similarity or similitude [9,14]. Similarity laws have long been known and are derived from the Buckingham Π theorem [15]. This theorem postulates that a problem can be expressed using any number of variables X_k and then restated in terms of a number (j) of independent physical units; usually mass, length and time. The redefinition of the problem is generally done by constructing a series of dimensionless numbers (Equation (1)) where the exponents (a_j) are rational numbers.

$$\prod\nolimits_i = X_1^{a_1} X_2^{a_2} \ldots X_j^{a_j} \tag{1}$$

Traditional dimensional analysis uses the words prototype and model to describe the experiment at different sizes [9,16,17], throughout this work the term prototype will refer to the subject, structure or event at actual size (i.e. the size for which the actual structure is designed); while the term model, is used to designate the prototype modified in size by a scale factor. In more recent times the word model is generally used to reference a computer model, computer simulation or finite element representation. To avoid confusion the term numerical simulation is used in this study to reference the finite element representations of the physical model or prototype structures.

For the purpose of obtaining the proper response in the scaled model, Oshiro and Alves [10–12] incorporated strain rate effects by defining a new base for the set of dimensionless numbers in terms of the impact mass G, the initial impact velocity V_0, and the dynamic yield stress of the material, σ_d, instead of the traditional mass, length, and time (MLT) base used in the similarity laws. The Π numbers (Equation (2)) that describe the event were manipulated to define Equation (3), so the model could be corrected for strain rate effects:

$$\left[\frac{A^3 G}{V_0^4 \sigma_d}\right]_{n1}, \left[\frac{T^3 \sigma_d V_0}{G}\right]_{n2}, \left[\frac{\delta^3 \sigma_d}{G V_0^2}\right]_{n3}, \left[\dot{\varepsilon}\left(\frac{G}{V_0 \sigma_d}\right)^{1/3}\right]_{n4}, \left[\frac{\sigma}{\sigma_d}\right]_{n5} \tag{2}$$

The dimensionless numbers presented in Equation (2) are defined in terms of the following variables: displacement (d), strain rate $(\dot{\varepsilon})$, acceleration (A), time (T), impact mass (G), force (F), Impact velocity (V_0), stress (σ) and dynamic yielding stress (σ_d).

$$\beta_{v0} = \sqrt{\frac{f\left(\beta_{v0}\dot{\varepsilon}_m^{nc}\right)}{f\left(\beta\dot{\varepsilon}_m^{nc}\right)}} \tag{3}$$

In the previous expression: f is a mathematical function that describes the constitutive model characterizing the material behavior in terms of strain rate; β_{V0} is the scale factor to determine the proper impact velocity for the model, β is the geometric scale factor for the experiment; and $\dot{\varepsilon}_{nc}^{m}$ the strain rate in the model (scaled experiment) that has not been corrected for strain rate effects. Oshiro and Alves used an iterative process to obtain the proper scaling factor for the velocity, in this process the model is scaled by a factor β, and from this scaled event a non-corrected strain rate $\dot{\varepsilon}_{nc}^{m}$ is obtained. This non-corrected strain rate is used to calculate β_{V0} and then a new impact velocity can be calculated. The process is repeated iteratively if necessary until convergence is achieved; further details can be found in Refs. [10–12]. In the present study, this iterative process was circumvented with no error by approximating the value of the strain rate in the "non-corrected model" to perform the calculations of the scale factor for velocity by using the impact velocity of the prototype and a characteristic length in the model.

In this study, the investigations were focused on axial crush tubes since this represents a challenging impact scenario to address with adhesively bonded structures, and there is a significant amount of data in the literature for these structures. The study is organized in three sections: section 2 discusses the validity of NDS