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Hybrid foetus with an FE head for a pregnant occupant model for vehicle safety investigations

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ABSTRACT

'Expecting', a computational pregnant occupant model, developed to simulate the dynamic response to crash impacts, possesses anthropometric properties of a fifth percentile female at around the 38th week of pregnancy. The model is complete with a finite element uterus and a multi-body foetus which is a novel feature in models of this kind. In this paper, the effect of incorporating a foetus with a finite element head into 'Expecting' is investigated. The finite element head was developed using detailed anatomic geometry and projected material properties. Then it was integrated with the 'Expecting' model and validated using the lap belt loading and the rigid bar impact tests. The model is then used to simulate frontal impacts at a range of crash severities with seatbelt and airbag, seatbelt only, airbag only as well as no restraint cases to investigate the risk of placental abruption and compare it with the model featuring the original multi-body foetus. The maximum strains developed in the utero-placental interface are used as the main criteria for foetus safety. The results show comparable strain levels to those from the multi-body foetus. It is, therefore, recommended to use the multi-body foetus in simulations as the computation time is more favourable.

1. Introduction

The first computational pregnant occupant model, 'Expecting', which includes a detailed 38-week-old multi-body foetus as well as finite element (FE) uterus and placenta, was developed and reported by Acar and Van Lopik [2]. The model used pregnant female anthropometry based on measurements of over 100 pregnant women [4,5]. It was demonstrated by Acar et al. [1] through crash simulations that the inclusion of a foetus in the uterus had a significant effect on the strain levels in the utero-placental interface (UPI).

The foetus in 'Expecting' is a 15-element multi-body model with kinematic joints, and hence, the head does not deform. A deformable head may change the dynamics of the system and therefore can affect the stress and strain levels in the uterus. The aim of this study is therefore to determine if the finite element foetus head instead of a rigid head makes a significant difference in the strain levels in the UPI.

1.1. The pregnant occupant model: 'Expecting'

The anthropometric data from pregnant women volunteers were used in the development of 'Expecting'.

Forty-nine different measurements of 107 women were recorded [5]. The measurements used the standard postures and procedures, as in [9] and [17], but were adapted where necessary to suit the pregnant body. A detailed multi-body foetus model composed of 15 rigid bodies interconnected by kinematic joints was integrated into the finite element uterus of the model. Two spherical joints with three rotational degrees of freedom are defined at the neck ellipsoid, one at the neck to connect it to the head, the other at the lower neck to connect it to the thorax. Spherical joints are also used to define the hip, ankle and shoulder joints. The multi-body foetus is placed inside a finite element uterus together with a fat layer surrounding its outer surface and a placenta at the fundal position. The finite element uterus model was built to provide a snug fit around the foetus representing 38-week pregnancy. The total foetal mass was 3.3 kg and the resulting total mass of the uterus with the placenta and the foetus is approximately 4.6 kg. The development and validation phases of Expecting and further details of the foetus development can be found in [2] and [3], respectively.

The model was then placed within a typical vehicle interior model, consisting of a seat, vehicle floor, pedals,

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bolsters and steering wheel in the multi-body/finite element software package MADYMO [13].

2. Methodology for the finite element head development

The computational pregnant occupant model, 'Expecting', which embodies the complexity of pregnant women's anatomy and a 38-week multi-body foetus in finite element uterus is used in this research. The strategy adopted in this study is to modify the model to change the foetus head to a finite element head, where the rest of the foetus remains as a multi-body model. Then, both models are used in numerous crash test simulations to compare the effect of the foetus with rigid body head and FE head on the strains generated at the UPI.

2.1. Anatomy of foetus head

The human head anatomy includes several layers including a stiff bony skull and soft tissue such as the scalp and brain, all with different material and anatomic properties. There are many studies on biomechanics of adult human head as early as 1950s [8,18]. These anatomical data were used in developing a number of different finite element head models that were used to investigate adult human head injuries [21,24,26]. However, in contrast to the adult head, there are very few studies investigating the biomechanics of the foetus head.

Most studies that involve modelling of pregnant woman for vehicle safety do not include a foetus. Some include only a rigid body representing the foetus. For example, Auriault et al. [6] used a whole body finite element model based on a 50th percentile 26 weeks pregnant woman to simulate a number of road vehicle accidents. In their model, the foetus was reported to be modelled as a homogeneous entity not differentiating between its components. Only other studies of foetus head modelling focus on birth process. Lapeer and

Prager [12] developed a foetal head model to study the head moulding during the first stage of labour which allows foetus head form to the geometry of the passage. Silva et al. [22] also constructed FE foetus model to study the effect of head moulding on the biomechanical behaviour of the pelvic floor muscles, during vaginal delivery. There are studies investigating injuries which focus on child head rather than foetus head. The most relevant study includes six-months-old baby head model by Roth et al. [19] to compare the effect of impact and vigorous head shaking. Recently, an FE model of a new-born infant's head was developed from high-resolution computer tomography scans by Khalid et al. [11] to be used in childhood injuries.

The bones and skeleton system of the foetus develop rapidly in the final trimester of the pregnancy. Head of the foetus undergoes structural and morphological developments. Skull of the foetus becomes stiffer and heavier. The head becomes the heaviest part of the foetus. The foetus head with approximately 1 kg mass and its large volume might play a significant role within the abdomen of the pregnant woman in the event of an impact.

The foetus head consists of scalp, skull and brain layers from exterior to interior (Figure 1). The brain is protected by the outer layers, mainly by the reasonably rigid skull of the foetus which consists of thin, flexible plates and soft bony tissue. There are four regions in the bony foetus skull. The frontal bones, the parietal bones, the occipital bone and face/base region. The skull of the foetus is thinner than the adult human skull and it includes a soft spot known as fontanel. This approximate 3×3 cm diamond shape area assists the bony regions of the skull to flex and allow the head of the foetus to pass through birth canal. Material properties of the fontanel are different than the foetus skull.

Ultrasound measurements of the biparietal diameter (BPD) and occipito-frontal diameter (OFD) are used to define the skull geometry (Figure 2). Snijders and
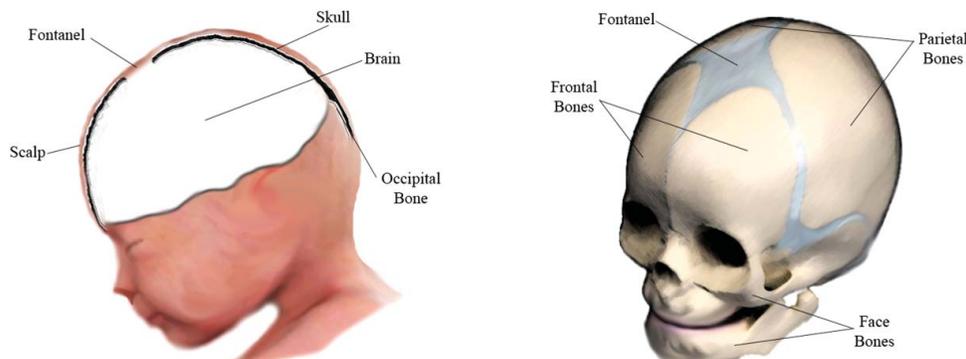

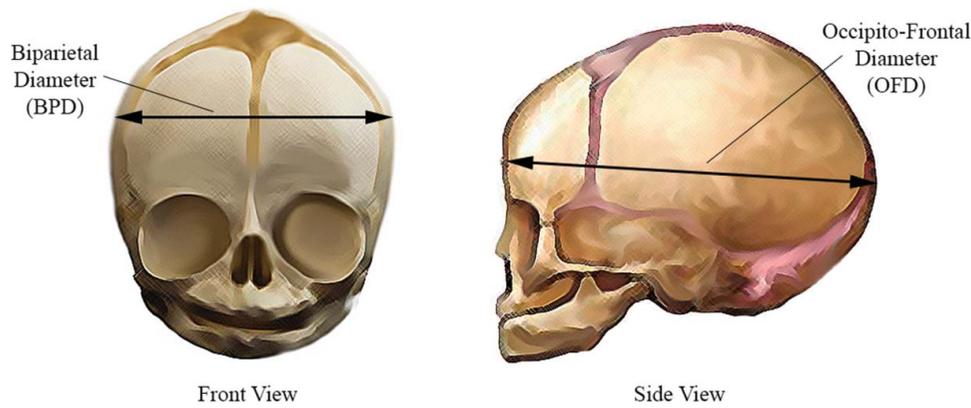**Figure 1.** Anatomy of foetus head.

Figure 2. Foetus head diameters.

Nicolaides [23] measured the head from the outer boundary of the skull and determined the mean BPD and OFD as 96 and 115 mm, respectively, for a 38-week-old foetus. Pheasant [17] investigated the head of newborns and found the mean head breadth (95 mm) and head length (120 mm). Head breadth is defined as maximum breadth of the head above the level of the ears. Head length is the distance between the glabella (the most anterior point of the forehead between the brow ridges) and the occiput (back of the head) in the midline.

2.2. Material properties

The material properties of the adult human head are well defined [15,25]. However, there is a dearth of publications that report the properties of a child's head [14]. Moreover, detailed investigation of the material properties of foetus head is the scarcest [3]. The foetus skull is reasonably flexible and deforms under external loading. Material properties, such as elastic modulus, Poisson's ratio and density, of the foetus head play a significant role in the biomechanical behaviour and hence determining the injury risks.

The foetus skull bones are heterogeneous and have viscoelastic material properties. However, the literature does not report heterogeneous and viscoelasticity properties. Therefore, the foetus skull model is simplified to be homogeneous, isotropic and with only elastic properties.

McPherson and Kriewall [16] derived the elastic modulus of foetal skull bone from three-point bending tests on 86 specimens. They indicated that elastic modulus and ultimate stress of foetus bones increased with gestational age. Coats and Margulies [7] tested the elastic modulus and ultimate stress of parietal and occipital bone specimens to failure in three-point bending tests as well. Three-point bending tests were conducted with human and porcine infant cranial bone specimens from 25 weeks gestation to six months of age [14]. Material properties for the

brain and fontanel are based on experimentally determined mechanical response of infant porcine brain tissue. The brain and fontanel are represented as linear viscoelastic solid and assumed to be incompressible with a bulk modulus of 2110 MPa. The data from [14] were used as a basis to obtain age-specific material properties for the 38 weeks foetus skull as summarised in Table 1.

2.3. FE head model

Anatomic geometry of the foetus head is taken as the reference geometry to develop the finite element head. Geometry of the ellipsoidal rigid structure of the multi-body foetus head and face in 'Expecting' is modified to form an integrated body for the FE head. The foetus is therefore represented as a hybrid model with 14 rigid bodies and one finite element head. The skull, fontanel and brain, which are the main anatomical features of the head, are incorporated into the model. Nodes and elements are created in HyperMesh (Altair HyperMesh 7.0 software) and then exported to the MADYMO. The finite element skull model is composed of four-node tetrahedral elements, which are more suitable for modelling complex bodies and surfaces than eight-node hexahedral elements. Two layers of these brick elements cover the fontanel at the top of the head taking up approximately 15% of the area (Figure 3). A homogeneous, isotropic brain is also represented with

Table 1. Material properties of 38-week foetus skull used in the model [11].

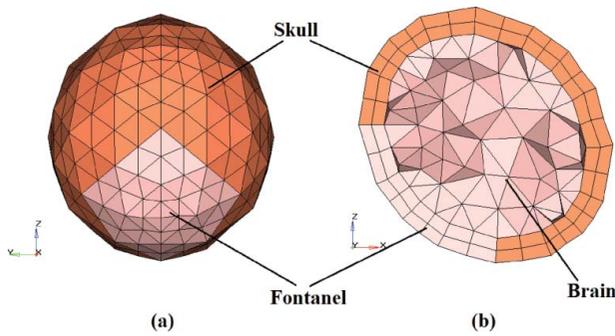|	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Skull	820.9	0.28	2150
Brain and fontanel	$G(t) = G_\infty + (G_0 - G_\infty) \times e^{-\beta \cdot t}$ $\beta = 0.09248$ s^{-1} with a bulk modulus $K = 2110$ MPa $G_0 = 5.99 \times 10^{-3}$ MPa $G_\infty = 2.32 \times 10^{-3}$ MPa		

Figure 3. Finite element foetus head: (a) front view; (b) side view.

tetrahedral brick elements inside the skull. The mass of the global head is approximately 1 kg.

3. Validation of expecting with hybrid foetus

The response of 'Expecting' with hybrid foetus in the uterus is validated using rigid bar impact and belt loading tests, the same tests used in the validation of the original 'Expecting' model [2].
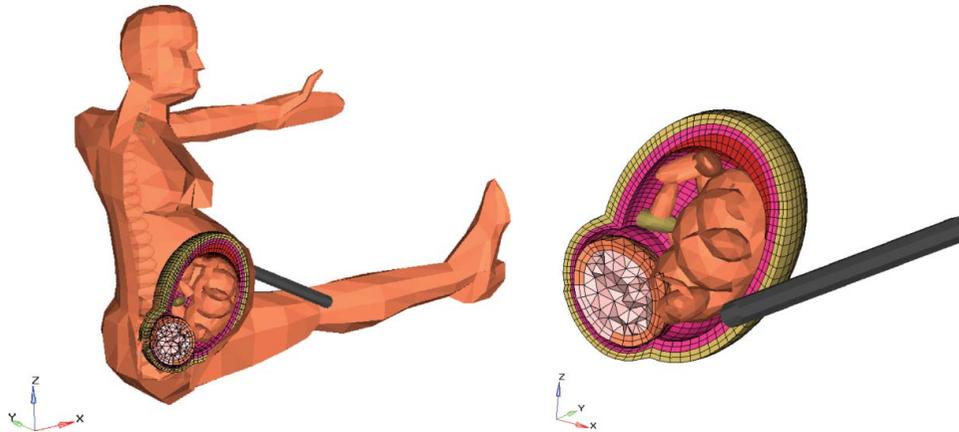
3.1. Rigid bar impact tests

The rigid bar impactor is a 2.54 cm diameter and 48 kg ellipsoid, based on the ballistic pendulum used by Hardy et al., which is applied at the approximate height of the umbilicus at 6 m/s (Figure 4).

The force–displacement response of the model to the 6 m/s rigid bar impact is shown in Figure 5. The rigid bar response corridors were developed by Hardy et al. [10] using 50th percentile male post-mortem human subjects. Rupp et al. [20] scaled these corridors to a fifth percentile female. Due to the lack of test data, there are no force–deflection corridors for pregnant women. Therefore, 'Expecting' with finite element foetus head is validated using rigid bar impact response corridors for the fifth percentile female subject.

Response of the model is comparable to the upper limit of the 6 m/s Cavanaugh corridor and well within the range of data from other researchers. The dynamic force–deflection response of the original 'Expecting' model is similar to 'Expecting' with the hybrid foetus model, as shown in Figure 5.
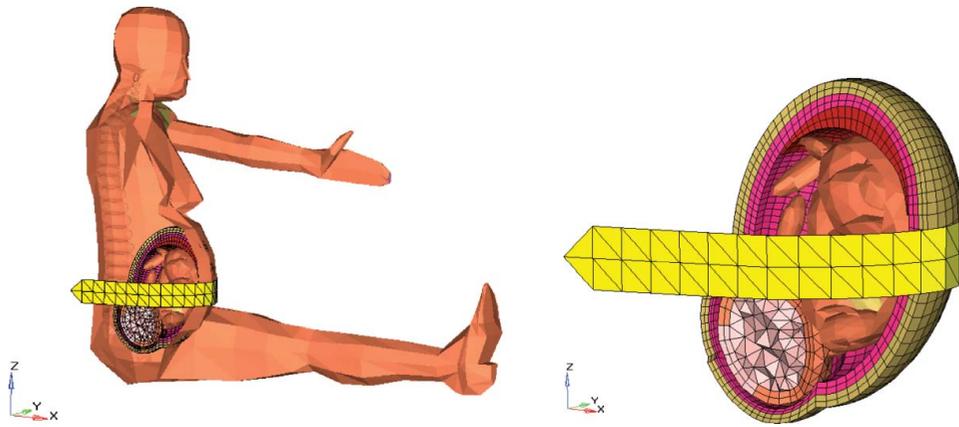

Figure 4. Rigid impact bar test for the 'Expecting' with the hybrid foetus.
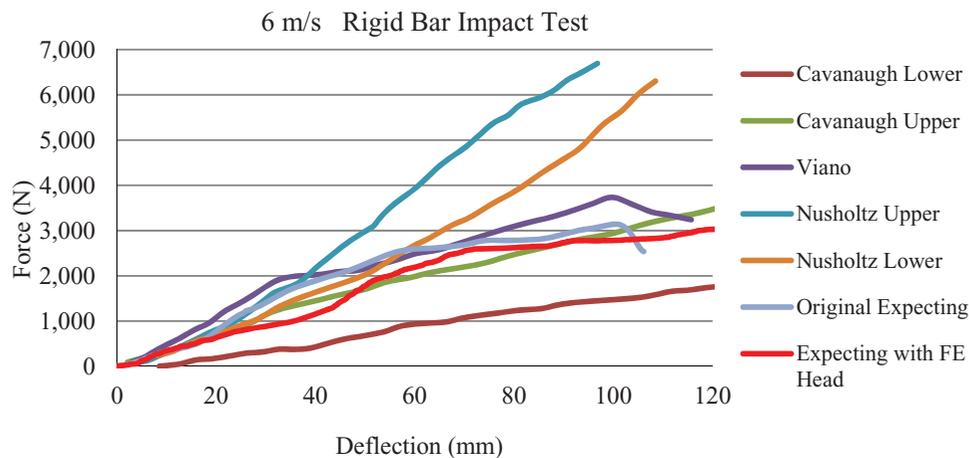
Figure 5. Hybrid foetus model rigid impact bar test.

Figure 6. Belt loading test for the 'Expecting' with the hybrid foetus model.

3.2. Belt loading

The belt-loading response corridor generated by Hardy et al., [10] is also used to validate the 'Expecting' with the hybrid foetus model. This corridor is developed from force–deflection data collected during simulated belt-loading tests on the abdomen of three post-mortem human subjects. In the model, the belt is used to apply a horizontal load to the abdomen of the seated pregnant occupant model through a length of belt webbing connected at both ends to a yoke-fixture. The belt-loading configuration is shown in Figure 6.

Force-deflection response of the pregnant abdomen of the 'Expecting' with the hybrid foetus to the 3 m/s belt-loading is within the corridor limits as shown in Figure 7.

4. Crash test simulations with hybrid foetus model

4.1. Simulation set-up

The modified 'Expecting' model with a foetus including an FE-head within MADYMO is used in the

same crash test simulations as used with the original 'Expecting'. Figure 8 shows 'Expecting' with the hybrid foetus within MADYMO for the fontal impact test configuration. The simulations include (1) 'seatbelt and airbag', representing a properly restrained pregnant driver; (2) 'seatbelt only', which excludes the airbag; (3) 'airbag only', which excludes the seatbelt and finally (4) 'no restraint' excludes both the seatbelt and the airbag. For each case, tests are run with crash speeds of 15, 20, 25, 30 and 35 kph with acceleration pulses of half-sine waves with 120 ms duration.

4.2. Injury criteria

For each simulation, the maximum von Mises equivalent strain levels at the UPI are determined for the 'Expecting' model with hybrid foetus to assess the risk of placental abruption, which is the main cause of foetal and occasionally maternal fatalities. These are then compared with the strain levels from the original 'Expecting' model.
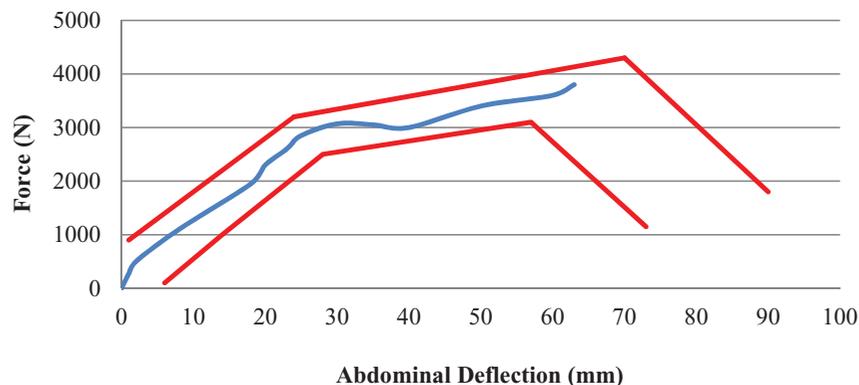

Figure 7. Force–deflection response of the 'Expecting' with the hybrid foetus model, to belt loading compared to scaled belt-loading corridors.
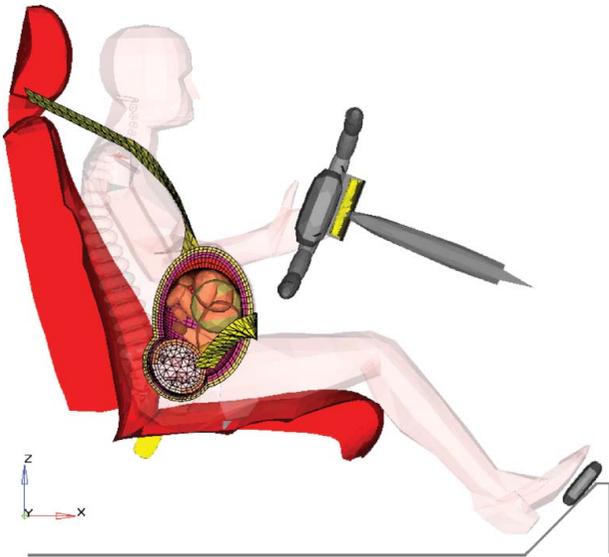
Figure 8. Typical frontal impact test configurations with the 'Expecting' including the hybrid foetus.

5. Results

The maximum strains at UPI from the original 'Expecting' model and 'Expecting' model with FE-head foetus are shown in Figures 9–12 for varying crash severities and restraint cases considered. Strains at the UPI are investigated to determine the placental abruption risk. The threshold strain value for the occurrence of placental abruption is widely accepted to be 0.60 at the UPI [20].

Both models predict similar maximum von Mises strain levels at the UPI at each simulation case considered. They also show that, as anticipated, the strains increase with crash speed.

For the fully restrained 'seatbelt and airbag' case, the maximum strains at the UPI are compared in Figure 9

to demonstrate the effect of FE-head foetus for varying crash speeds. For both rigid and hybrid foetus models, the maximum strains at UPI are in the safe region under the threshold value for the range of crash severities considered. For the speed of 15 and 20 kph, maximum strain at UPI for the original 'Expecting' is slightly higher than the model with the finite element foetus head, whereas after 25 kph, the hybrid foetus model generates higher strains at the UPI than the original model.

The 'seatbelt only' case results for the maximum strains at the UPI, follow a similar pattern to the strains in the 'seatbelt and airbag' case as shown in Figure 10, but are generally slightly higher. At the 35 kph speed, the strain level for the FE-head model slightly exceeds the critical threshold level whereas the multi-body model strain levels remain below the critical value.

The comparison of results from the 'seatbelt and airbag' case and the 'seatbelt only' case suggest that the airbag plays a minor but helpful role in reducing the strain levels when it is used in conjunction with the seatbelt.

For the 'airbag only' case, the maximum von Mises strains at the UPI from the simulation with the original 'Expecting' and the 'Expecting' with the hybrid foetus are compared in Figure 11. The original 'Expecting' with the multi-body foetus predicts slightly higher risks than the hybrid foetus model at all speeds. Both models demonstrate that the lack of seatbelt deployment causes a significant adverse effect to the risk levels.

For the 'unrestrained' case shown in Figure 12, both models give comparable strain levels at the UPI which are consistently above the threshold at all speeds considered predicting placental abruption risks. These results highlight that using no restraints carries a very high risk of placental abruption.
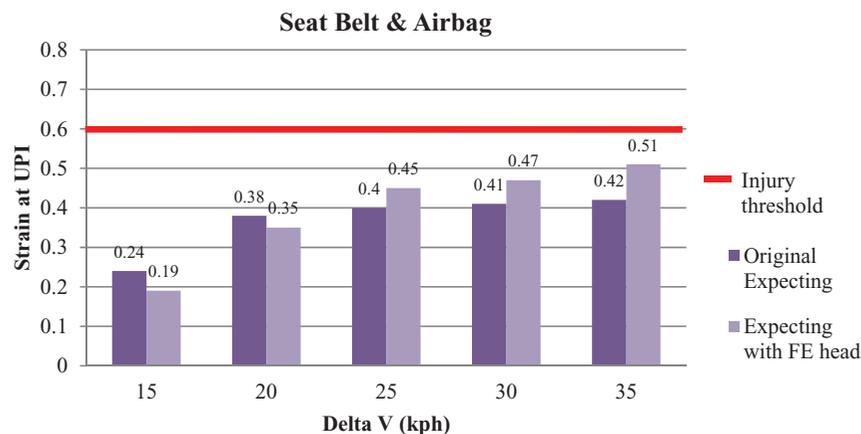

Figure 9. Comparison of the original 'Expecting' and 'Expecting' with the hybrid foetus model crash test simulation results for 'seatbelt and airbag' case.
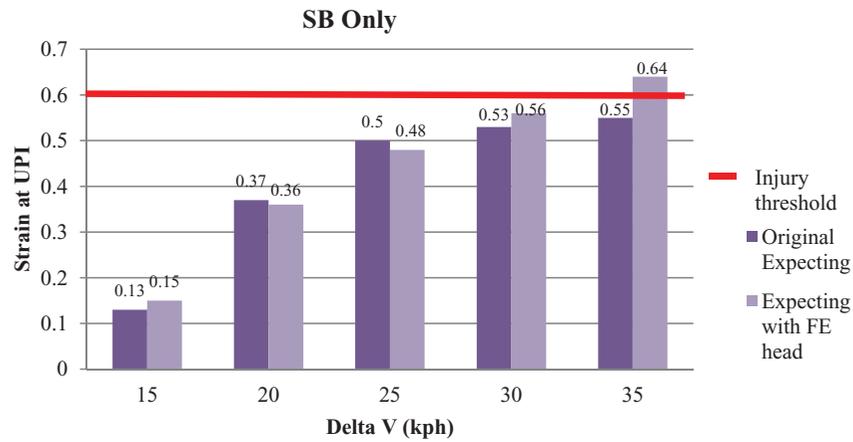
Figure 10. Comparison of the original 'Expecting' and 'Expecting' with the hybrid foetus model crash test simulation results for 'seatbelt only' case.
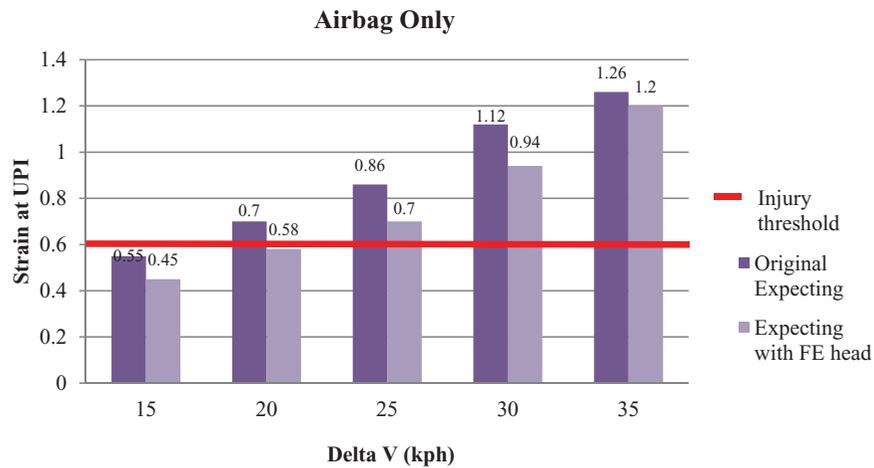

Figure 11. Comparison of the original 'Expecting' and 'Expecting' with the hybrid foetus model crash test simulation results for 'airbag only' case.
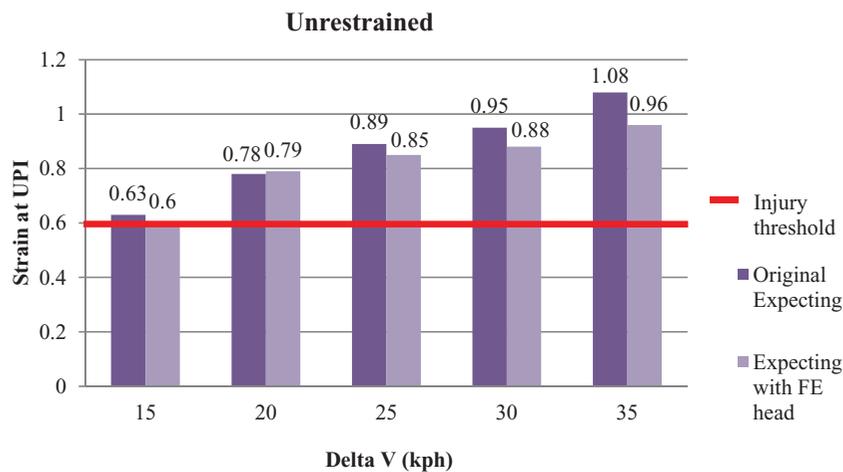

Figure 12. Comparison of the original 'Expecting' and 'Expecting' with the hybrid foetus model crash test simulation results for 'unrestrained' case.

6. Discussions and conclusions

In this research, implications of incorporating a finite element head into the multi-body foetus within 'Expecting', the pregnant occupant model. It should be noted that within the scope of this work, the injury risk is only assessed through arguably the most important criteria for foetus safety, the maximum strain levels at the UPI for placental abruption.

Crash test simulation results from 'Expecting' and 'Expecting' with an FE-head foetus show similar trends in all cases considered. The difference between the maximum strain levels at the UPI is reasonably small, which can be attributed to the position of the foetus head which fits snugly into the curve of the pelvis and there is little room for the head to move to significantly influence the dynamic response of the foetus as a whole to affect the strain levels in the UPI.

The simulation results reveal that the hybrid foetus model with an FE head produces different reaction forces to a certain degree and absorbs varying amounts of energy during impact situations when compared to the whole multi-body foetus model. This is clearly due to the deformable character of the FE head, which in turn affects the dynamic response of the foetus and the uterus to some extent. However, it is difficult to determine which model is more accurate. It can be speculated that 'Expecting' with a foetus with a deformable FE head represents a more realistic pregnant occupant model. The next stage of this research will consider converting the whole foetus to an FE model to represent the soft tissue and deformable bony tissue which potentially represents a much more realistic foetus. The aim would be to test the hypothesis that a whole FE foetus makes a difference to the dynamic behaviour of the foetus and uterus response and the predictions of placental abruption.

From the viewpoint of computational efficiency, the FE-head significantly increases the processing time required for the simulations. Therefore, it could be concluded that the multi-body foetus model, which gives not too dissimilar predictions for placental abruption risks for much shorter processing times, could be chosen over the hybrid model.

It is also concluded that both models confirm that the correct use of seatbelt in conjunction with the airbag provides the most effective protection for the foetus in frontal vehicle impacts. The findings also support that, whilst the seatbelt on its own without the airbag provides adequate protection, the airbag on its own without the simultaneous deployment of the seatbelt provides very little protection..

Disclosure statement

No potential conflict of interest was reported by the authors.

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