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COLLISION HANDLING OF FABRIC YARNS IN WOVEN STRUCTURES

Rimantas Barauskas, Mindaugas Kuprys

Department of System Analysis, Kaunas University of Technology
Studentų str. 50-407, LT-51368 Kaunas, Lithuania

Abstract. The paper deals with the modelling of the physical behaviour of woven structures imitating the textile fabrics. The model is based on a combined approach which presents longitudinal elastic properties of each yarn by a system of non-volumetric structural elements (springs), while the collision search and response algorithm works in a 3D space based on tight-fitting of the yarns by using oriented bounding boxes (OBB). The separation axis theorem (SAT) for collision detection between OBBs is performed. Collision response is performed by applying collision impulses to colliding nodes thus avoiding interpenetrations of the yarns. A simplified approach is applied in order to take into account the deformation of the cross-section of a yarn. It is assumed that the cross-sectional area remains constant all the time while its shape is elliptic with changing lengths of axes. Numerical examples of simulation of tension, warp and shooting-through the fabric are presented.

Keywords: finite elements, particle elements, textile, collision detection, collision response.

1. Indroduction

The problematic of the computational models for simulation of the textile structures is defined mainly by the necessity to present the behaviour of the material in two different length scales. At the macro-scale one is inclined to regard a fabric as a continuous membrane. At the same time a textile fabric is not a continuum as at the micro-level its behaviour is defined by the contact interactions of the yarns in the woven structure. The dimension of this micro-structural level is finite and may be very complex depending upon the properties of the yarn and of the weave. The continua based approximations of the fabric behaviour are always only rough approximations of the real fabric. Moreover, different continua-based models for modelling different situations (extension, warping, failure, etc.) may be necessary. Therefore the modelling of the fabric by directly including the weave geometry and physical behaviour into the model is preferable.

Implementations of the woven structure models can be performed by using the finite element method (FEM) computational environments such as LSDYNA, ABAQUS Explicit, DYTRAN, etc. The dimensionality of the obtained models is huge as each yarn has to be presented as the volumetric finite element structure. Moreover, in applications focused on the problem-specific area of the simulation of the physical behaviour of a fabric, significant model implementation efforts are necessary. Therefore the development of more efficient "physically-based" approximate models of a yarn structure is an important issue at the present time.

One of the simplest physically-based models at the same time allowing closest to the real-time performance is the mass-spring system. The concept of a yarn as of the structure assembled of a pin-connected rod-elements chain was presented in [9]. The drawback of the approach was that the cross-sections of the yarns remained unchanged during the deformation of the fabric weave. In [8] a new approach referred to as "multi-chain digital element analysis" has been presented. The main idea was to represent a yarn as an assembly of fibres. Each fibre was modelled as a chain of elastic rods, and a yarn was modelled as an assembly of such chains. The drawback of the model is that the weave has been presented in a 2D space while the number of the nodes of the model was huge if cloth models of realistic dimensions have been considered.

Collision detection and response is an essential part of the simulation process. Dealing with deformable bodies is the main time consuming stage of the computation covering both collision search and response among colliding parts of yarns. The technique based on the usage of oriented bounding boxes (OBBs) and the separation axis theorem (SAT) has been described in [3, 4]. In the case of deformable bodies it requires significantly more time for updating the OBBs at each time step comparing with rigid bodies collision analysis where the bounding volumes are prepared during the pre-processing stage. Collision detection is performed by using the SAT algorithm and the tight-fitted OBBs that fully enclose the yarns.

The bottleneck of the collision handling algorithm is to avoid interpenetrations of the yarns. Commonly used penalty-forces method is not applicable because of high frequency oscillations inevitably arising because of the penalty stiffness. The impulse and momentum based method is based on ”instantaneous” change of velocities of contacting elements.

The focus of this paper is the development of the efficient model of the fabric as woven structure. We propose a new approach for estimation of volumetric yarns by using combined particles (CP) for presenting them as volumetric structures. A CP is a two-mass system linked by a spring, however, geometrically they are considered as cylindrical elements at the initial stage. As the deformation of the weave takes place the circular cross-sections of the yarns are allowed to change their shape and become elliptic. So, the approach is a compromise between the simplified uni-dimensional rod system and a fully volumetric model of a yarn in a weave. It enables to achieve good performance along with the possibility to analyze the deformable yarn structure in a 3D space.

The rest of the paper is organized in the following way. The next section presents the geometrical model of a fabric including an internal structure of yarns as well as fabric weaving and replication algorithms. The physical model of the woven pattern is presented in the third section. It explains the basic steps of the CP adaptation for the textile fabric modelling, as well as, internal and external forces acting on the fabric. Sections 4 and 5 cover the collision handling problems. The collision detection algorithm is presented in Section 4 and OBBs as bounding volumes used for tight-fitting of the yarns are introduced. At this stage the collision time instant, the colliding points and the interpenetration vector is obtained. The collision response of contacting nodes and deformation properties of the cross-sections of the yarns are presented in Section 5. The last section illustrates the results obtained by the proposed model. It deals with the extension of the initially over-crimped yarns and the failure of the fabric during the contact with a rigid body.

2. Geometrical model of a fabric

2.1. Yarns in a fabric

The mechanical behaviour of woven textiles can be investigated at different scales of length. The scales are determined by several characteristic dimensions: a diameter of a fibre ~10^{-5}m, a diameter of a yarn ~10^{-3}m and the linear dimension of the sheet of the fabric under investigation >10^{-1}m. The layout of the interwoven yarn structure is comprised by two mutually perpendicular yarn system referred as warps and wefts (Figure 1). Generally, a weave of a fabric is determined by a prescribed pattern of crimped yarns.

The geometrical shape and sinuosity of yarns as 3D objects is quite complicated. It is unique for each kind of yarns and the weave patterns and depends upon many factors, such as mechanical properties of the yarn, technique of weaving, inter-yarn compression, etc. Finite elements models of a weave are obtained by considering a yarn as a 3D solid body. It leads to huge dimensionality of the model and is undesirable if the computational time is of primary importance. On the contrary, presenting the yarn as a chain of rod elements of a constant cross-section leads to over-simplification and loss of adequacy of the model. Our way of developing the model considers yarns as flexible uni-dimensional components (combined particles) of the circular cross-section.

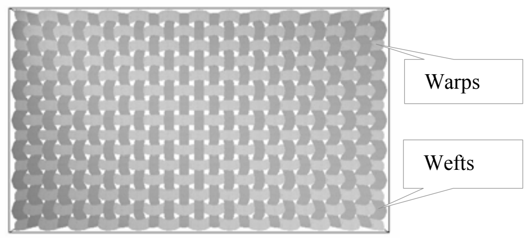
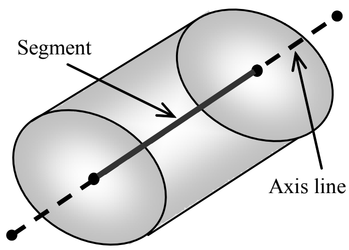
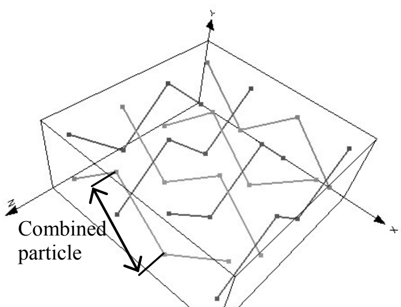


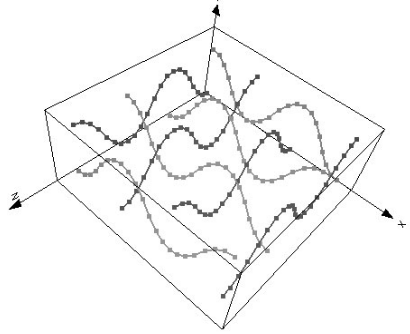
Figure 1. Plain weave



a) Combined particle



b) CP in the yarn



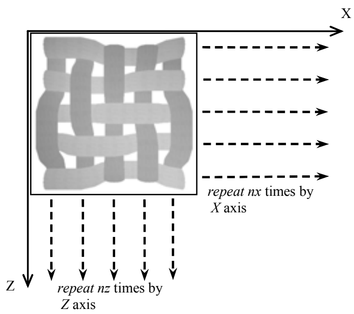
c) smoothed yarns

Figure 2. Crimped yarns assembled of CPs

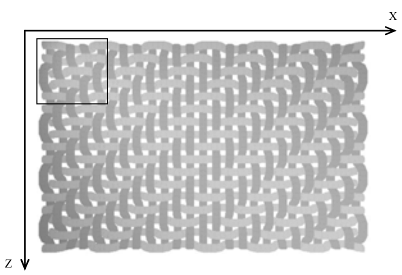
2.2. The model of the weave

Geometrically the CP is a segment of a yarn (Figure 2a). Obtaining a weave of a particular pattern is based on the determination of positions of each CP with a respect to other CPs (Figure 2b). In this way models of different kind of weave patterns may be obtained. At the same time it perfectly suits for implementing the physical model of the fabric. Unfortunately, weaving is toil and time consuming work, especially keeping in mind that the real dimensional fabric contains thousands of yarns, besides yarns assembled of rough elements look "unnatural", so we are processing the following actions to solve these problems.

The smooth curves of crimped yarns are obtained by means of B-spline approximation (Figure 2c). Depending on the desirable level of smoothness extra nodes are added inside of the initial CP thus obtaining a new shape closer to natural. Trying to save some time weaving is performed during the pre-processing step together with so called fabric "replication" step. In order to completely describe the particular kind of the weave the small piece of the pattern is enough (Figure 3a). The model of the fabric of real dimensions is obtained by replicating the piece of the fabric in two directions (Figure 3b).



a) A piece of a fabric describing the pattern weave



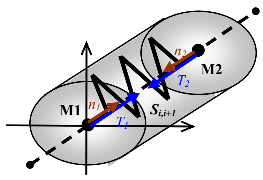
b) the extended fabric obtained after replication step

Figure 3. Plain weave

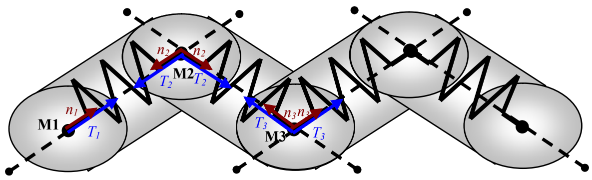
3. Modelling the physical behaviour of a fabric

3.1. The physical structure of the yarns

The physical model of a single CP consists of two nodes linked by a spring (Figure 4a). We assume that the mass of the CP is lumped at the ends of the CP. A yarn is composed of a chain of such elements (Figure 4b). Volumetric yarns have longitudinal and through-thickness stiffness. Longitudinal stiffness of a yarn is determined by an elasticity modulus of the material and the cross-sectional area of a yarn. As an example, the longitudinal elasticity modulus of the sample paraaramid yarns is 90GPa and their elongation at the failure threshold is about 3-5%.



a) Physical CP



b) part of the multi-chain

Figure 4. Physical structure of CP

The cross-section of a multi-filament yarn is composed of cross sections of very thin fibres comprising the yarn. Practically, the change of the yarn's cross-sectional geometry takes place because of the internal re-distribution of fibres inside of the yarn. Therefore the through-thickness deformation of a yarn is mainly dependent upon the interaction properties of filaments inside a yarn and only very slightly upon the elasticity modulus of the material. Practically only empirically determined values of coefficients can be used in order to present the through-thickness stiffness of an element. The cross-sectional deformation model in more detail is presented in Section 5.2.

3.2. External and internal forces

Assume that CP is composed of two nodes $\mathbf{M}_i$ and $\mathbf{M}_{i+1}$ linked by a spring $S_{i,i+1}$. The node $\mathbf{M}_i$ is at position $\mathbf{M}_i^{X,Y,Z}(t)$ at time instant t. The evolution of a system is governed by the 2nd Newton's law

$$\mathbf{F}_i(t) = \mu_i \mathbf{a}_i(t) \tag{1}$$

where μ_i, $\mathbf{a}_i$ – mass and acceleration of the node $\mathbf{M}_i$.

The force acting upon node $\mathbf{M}_i$ consists of *external* and *internal* components:

$$\mathbf{F}_i(t) = \mathbf{F}_i^{EXT}(t) + \mathbf{F}_i^{INT}(t) \tag{2}$$

where $\mathbf{F}_i^{INT}, \mathbf{F}_i^{EXT}$ – sum of all internal and external forces acting on the *i-th* node, respectively.

Internal force $\mathbf{F}_i^{INT}$ exerted upon node $\mathbf{M}_i$ consists of forces generated by the neighbouring elements. The force magnitude in the direction $\mathbf{n}_i$ reads as

$$\mathbf{F}_i^{INT}(t) = \sum_{k \in \Re} \mathbf{n}_k F_k(t) \quad (3)$$

where $F_k(t) = K(l_0 - l) - c\mathbf{n}(\mathbf{V}_{i+1}(t) - \mathbf{V}_i(t))$, K – stiffness of the spring; l – length of the element; l_0 – initial length of the element; c – damping coefficient; $\mathbf{V}_i$ – velocity of the *i-th* node; $\Re$ – the set of all neighbouring nodes.

The external force is determined by the kind of the load to which the model is to be exposed.

4. Collision detection

The handling of inter-element collisions is the most time consuming part of the simulation process due should be performed at each time instant. The model is implemented in 3D, so collision handling among yarns is treated by considering them as volumetric objects.

Broad and narrow phases of the collision detection are distinguished. During the broad phase OBBs of the pairs of the object overlapping in the time interval are detected. The fabric yarns are composed of many parts, the so-called elements, bounded by the OBBs, and require a bounding-volume hierarchy for quickly culling the non-colliding pairs of primitives. Commonly bounding-volume hierarchies are static structures and are computed once at the pre-processing step and cannot be modified. However, in our application deformable structures such as fabrics are simulated and bounding-volume hierarchies should be fast updated at each time instant.

As long as potentially colliding pairs are found the narrow collision detection phase is performed. In this phase, pairs for exact collisions are tested. Depending on the desired type of response, our application will determine the first time of the contact, the contact points and the normal at the earliest contact place or the translation distance (TD) vector. The TD vector is the shortest translation that brings the objects in the touching contact. It is useful for determining the contact data in the case of the interpenetration. Each of the presented terms is discussed in details in the following sections.

4.1. Bounding of elements

Mostly used "collision proxies" of potentially colliding elements are: *axis aligned bounding boxes* (AABB), *oriented bounding boxes* (OBB), *spheres*, etc. The choice governed by these constraints: it should fit the original model as tightly as possible; testing two such volumes for overlap should be as fast as possible; it should require the bounding volumes updates as infrequently as possible. Considering all advantages and disadvantages provided by these bounding volumes the OBBs were chosen.

4.1.1. Oriented bounding boxes

An OBB is defined by a center $\mathbf{C}$, a set of right-handed orthogonal axes $\mathbf{A}_0, \mathbf{A}_1, \mathbf{A}_2$ and a set of positive extents e_0, e_1 and e_2 (fig.5a). As a solid box, the OBB is represented by

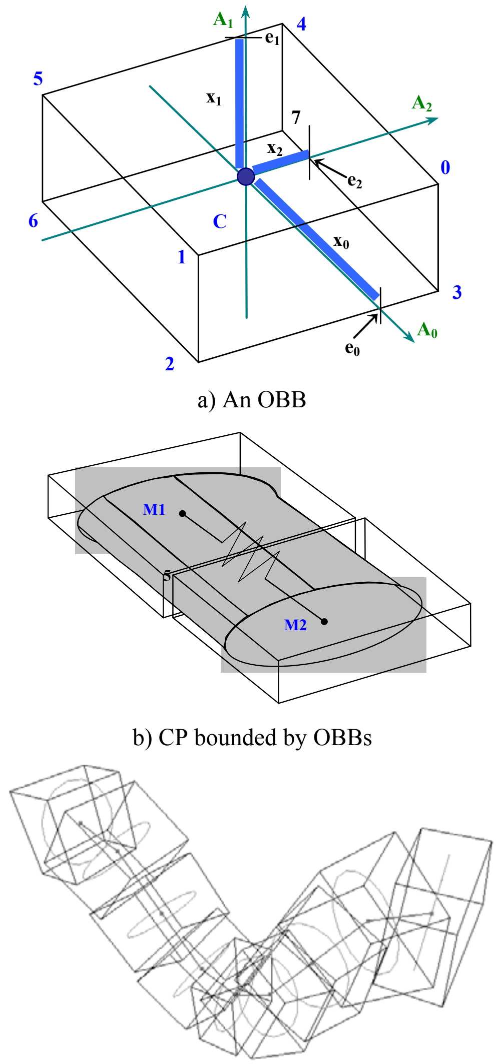
$$\left\{ \mathbf{C} + \sum_{i=0}^{2} x_i \mathbf{A}_i : |x_i| \le e_i \forall i \right\}$$

where x – points on the axes. The eight vertices of the box are

$$\mathbf{C} + \sum_{i=0}^{2} \xi_i e_i \mathbf{A}_i$$

where sign ξ_i may take values 1 or -1.

An example of the CP and the yarn bounded by OBBs are presented in Figures 5b and 5c respectively. The piece of the fabric bounded by the OBBs is presented in Figure 6.



a) An OBB

b) CP bounded by OBBs

c) yarn bounded by OBBs

Figure 5. Bounding volumes in the model

4.2 Intersections testing of OBBs

Testing of intersection among several convex polyhedrons (OBBs) is performed by applying the separation axis theorem which states that if exist a line for which the intervals of a projection of the two objects onto that line do not intersect then the objects do not intersect too. Such a line is referred to as a separating line or, more commonly, a *separating axis* (SA) [3]. The algorithm intends to determine whether it is possible to fit a plane between two objects. If such a plane exists, then the objects are separated, and cannot intersect. To determine if the objects are separated, it is simply a matter of projecting the objects onto the normal of the plane and checking if the intervals overlap [7]. If a SA is found, the remaining ones, of course, are not processed. The intersection testing process for two OBBs requires comparing 15 potential SA: 6 for the independent faces of two OBBs and 9 generated by an edge from the first OBB and an edge from the second OBB. The "quick out" from the intersecting testing procedure takes place if the SA is found.

The algorithm is formulated for the intersection testing of objects as if they were stationary, however, it can be applied for moving objects as well. If an object is assumed to have a constant velocity during each time step, the extension of the algorithm to the case of moving objects is mathematically straightforward. Intersection testing of moving objects is identical to the intersection testing of the moving intervals of the projection on the potential separating axes. If the two time-dependent projection intervals are $[u_0(t), u_1(t)]$ and $[v_0(t), v_1(t)]$, then the objects do not intersect during the time interval $t_{\min} \le t \le t_{\max}$ if $u_0(t) < v_1(t)$ or $v_1(t) < u_0(t)$ for all $t \in [t_{\min}, t_{\max}]$. An additional interest for moving objects is to determine the interpenetration depth and the contacting points of the intersection of the objects during the specified time interval [4].

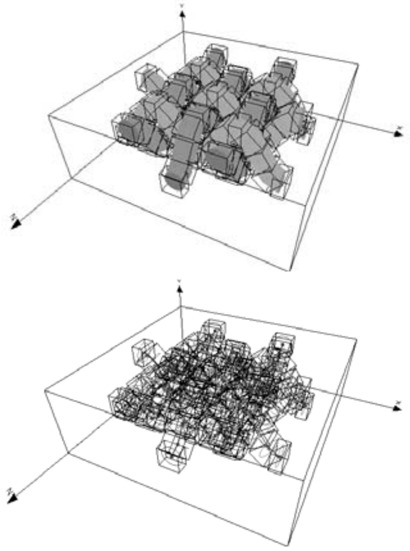


Figure 6. Yarns bounded by OBBs

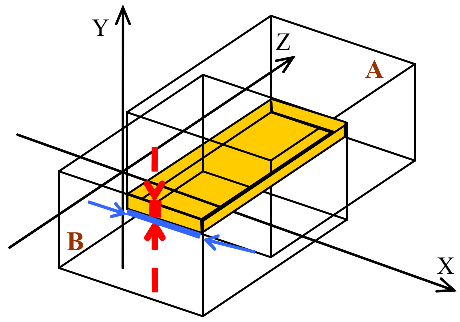


Figure 7. Overlapping bounding boxes

4.3. Finding the translation distance

After a collision is detected, a slight inter-penetration of OBBs always takes place. The SA method can be used to find the interpenetration depth and the direction required to push the OBBs apart with a little bit of extra effort. A combination of both the *depth* and *direction* of intersection is referred to as the *translation distance* (TD), a dotted segment in fig.7. If objects intersect, we know the intervals calculated on each of the SA of each object. The projections of the intersection volume on the three coordinate axes provide possible "push-away vectors" that may be applied to each object in order to stop the interpenetration along that axis. In principle the objects may be pushed away along a freely selected axis, however, it is preferred to select it along the line with the minimum amount of the overlap. Such a vector provides the TD. The obtained interpenetration depth of the TD vector is used both for the calculation of the velocities of the nodes of the yarns and during the collision response step thus avoiding interpenetrations.

4.4. Finding contact points of intersection

Assume the first time instant of the intersection of OBBs is now detected. As the next stage the contacting points of the OBBs should be found. Two colliding boxes can have a contact in several ways: a single vertex with the polyhedron, an edge with the polyhedron, the polyhedron with the polyhedron, etc. For example, in Figure 8 we can see that the top face of the box B is colliding with the bottom face of the box A along Y axis. This simple example demonstrates the basic idea of the algorithm. The overlapping area of two OBBs is marked as a dashed rectangle combined of "supporting" points from 1 to 4. In order to obtain the contacting points from the overlapping area we perform a clipping procedure that clips one polygon against the other in order to find the common intersection patch. Other situations are analysed as follows: if an edge is resting on the polyhedron, we need edge points on the polyhedron as our contact information. In case of an edge versus another edge, then we need the points on both edges as contacting points. In case of a vertex against a polyhedron, simply the projection of the vertex onto the surface of the polygon is calculated [7].

5. Collision response

An interpenetration of elements violates the reality and requires applying expensive correction procedures. The collision response algorithm includes the measures for preventing interpenetrations and for rendering the cross-sectional shapes of the yarns. Suppose at the given time instant OBBs of two elements are overlapping. The simplest approach is to move them back to their previous positions. While this might be sufficient for programming of games, the physically based modelling should be based on the laws of physics. The collision response can be performed in three different ways using *penalty-forces*, *analytical* or *impulse-momentum* based methods.

The penalty method (PM) focuses on using the laws of Newtonian dynamics to simulate the collision handling. When a collision between yarn's elements takes place, common actions would be to apply two forces acting in opposite directions to both elements. The drawback of the approach is that forces cannot change the velocities instantaneously. Therefore several small time integration steps have to be performed until the interpenetration is prevented, at the same time small vibration of an elastic nature may occur at the contact point.

Analytical methods (AM) have the same idea as the PM and focus on the analytic calculation of the forces that would prevent contacting bodies from interpenetration. A method is proposed in [2] for the analytical calculation of the forces between systems of rigid bodies in static contact, however, it is not suitable in the case of deformable bodies such as yarns the geometrical shape and sinuosity of which are complicated.

The impulse-based method (IM) is based on the impulse-momentum principle. It enables to calculate instantaneous changes of velocities of two bodies caused by the contact interaction [1].

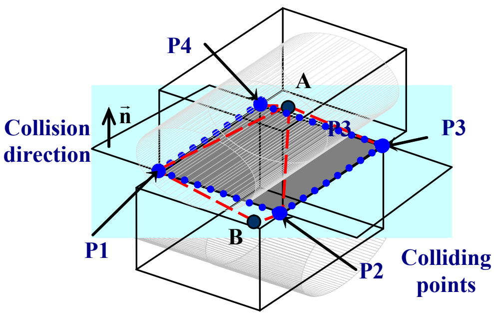


Figure 8. Parts of yarns bounded by OBBs in resting contact

5.1. Collision response of OBBs

As a result of the collision detection step, we have found the contact points and the TD vector. We investigate two colliding OBBs labelled A and B (Figure 8). The contact takes place when a point of A touches a point of B with a *negative relative velocity* in TD direction [6]

$$VR^{Pi} = (\mathbf{V}^{APi} - \mathbf{V}^{BPi}) \cdot \mathbf{n} \quad (4)$$

where $i \in [1,$ number of colliding points], $\mathbf{V}$ – velocity of the particular point.

Consider three cases:

1. If $VR^{Pi} > 0$, the points are leaving each other and we can ignore them;
2. If $VR^{Pi} = 0$, the points are in resting contact;
3. If $VR^{Pi} < 0$, the interpenetration tends to increase ant should be stopped.

In the third case the collision is handled as follows:

1. The TDs of colliding OBBs are computed (it indicates the relative cross-section deformation of a yarn);
2. The cross-sectional shapes of the yarns at the contact zone are changed;
3. If the amount of cross-sectional deformation is less then defined maximum cross-sectional deformation (MCD) then go to steps 1 and 2;
4. Else, the collision response algorithm is applied. It means we do not let the OBBs penetrate each other any more).

The time interval when the collision occurs and the interpenetration begins is very short. It may be assumed that during the single time integration step "instantaneous" change of velocities of the nodes takes place in such a way that at the next time moment both nodes move together. The magnitude of the interaction impulse relates the incoming and outgoing velocities depending upon the value of the coefficient of restitution. The assumptions that yarns do not spin about their axes and no contact friction exists are made. The equation derived in [6] to compute the impulse magnitude is used as

$$j = \frac{-(1+e)\mathbf{v}_1^{AB} \cdot \mathbf{n}}{(1/m_A + 1/m_B)} \quad (5)$$

where e – coefficient of the impact velocity restitution; $\mathbf{n}$ – collision direction; m – mass of the node.

If two OBBs A and B collide, the impulse vector $j\mathbf{n}$ acts upon A and the opposite vector $-j\mathbf{n}$ upon B.

5.2. Deformations of the yarns

Under application of loads yarns can be deformed in longitudinal and through-thickness directions. In our model the longitudinal deformation is strongly based on physical properties of the material while the through-thickness deformation is evaluated geometrically. We assume that the cross-sectional shape of the multi-filament yarn may change significantly from nearly circular to fully elliptical until a threshold of redistribution of filaments over the cross-section is reached. Forces necessary to change the cross-sectional shape at the initial stage of deformation can be assumed to be very small as they actually do not cause the deformation of the material. After the cross-section is deformed to the threshold value, the further change of the shape is locked. We are using the term *maximum cross-sectional deformation* (MCD) in order to describe the threshold value. Empirically we set the value to 50%-70%. As long as the deformation of a yarn reaches the MCD, the impulse-momentum principle is applied in order to handle the velocities of contacting nodes. The drawback of the approach is that the selected values of MCD are not fully reliable; however, they may be better estimated by comparing the results of simulation of a real fabric against the experimental ones.

5.2.1. Longitudinal deformation of the element

The longitudinal deformation of the CP depends upon the stiffness of the yarn and upon forces acting at the nodes. The equation specifying the spring force vector acting at a point i reads as

$$\mathbf{F}_i = \sum_{j \in \Re} k_{ij} \left(l_{ij} - \left\| \mathbf{u}_i - \mathbf{u}_j \right\| \right) \frac{\mathbf{u}_i - \mathbf{u}_j}{\left\| \mathbf{u}_i - \mathbf{u}_j \right\|} \qquad (6)$$

where $\mathbf{u}$ – shift of the node; $\Re$ – all neighbouring nodes, k_{ij} – the elastic constant, l_{ij} – the length of the non-deformed spring.

5.2.2. Cross-sectional deformation of the element

The calculation of the cross-sectional deformation of the element is performed at its nodes and the amount of the deformation is based upon the relative interpenetration depth. The interpenetration depth is found from the TD vector (Section 4.3). The cross-sectional shape of a multi-filament yarn may change significantly from nearly circular to elliptical (oval). Here we propose an empiric model for evaluating the deformation of the cross-section of the element based on the assumption that mutation from a circular to elliptical shape is performed by changing their radii as:

$$r_{new}^X = r^X + r^X \varepsilon_{node}$$

$$r_{new}^Y = r^Y - r^Y \varepsilon_{node}$$

where ε_{node} – deformation of the node various in interval (0,1) (fig.9) and vice versa in opposite direction. The relative deformation ε_{node} at time instant t is evaluated as:

$$\varepsilon_i^{AXIS}(t) = \frac{\Delta r^{AXIS}}{r^{AXIS}}$$

where Δr^{AXIS} – radius at any time instant, r^{AXIS} – natural radius of a yarn.

Dependent on the loads, yarns interact among themselves continuously. As a result the cross-sectional shapes of the yarns continuously mutate. As soon as the deformation of the yarn exceeds the specific MCD threshold the mutation progress stops. The defined MCD threshold of a yarn is presented as black ellipses in Figure 10c. It means that yarns can not deform any more along the collision direction. A simplified approach representing the squeezed yarns based on computation of relative deformations among yarns is used in the current implementation.

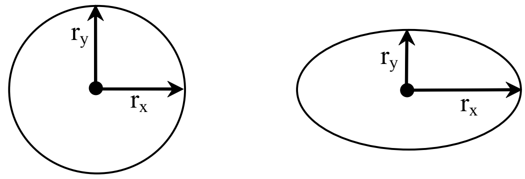
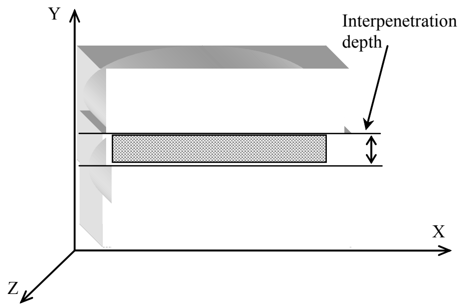
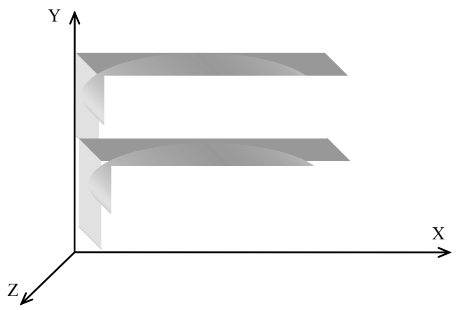


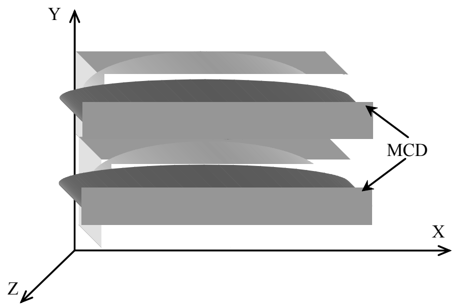
Figure 9. Mutation of the element cross-section from a circle to an ellipse



a) Overlap distance of the OBBs



b) view of the cross-shape during compression



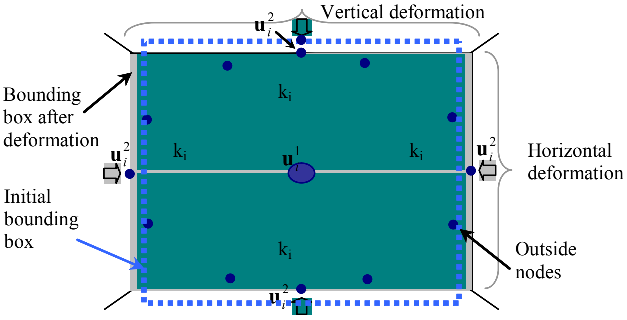
c) MCD threshold of a yarn

Figure 10. Cross-shapes of deformed yarns

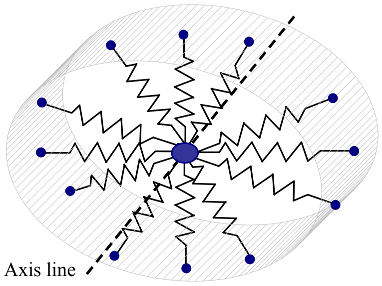
The computational model of the cross-sectional deformation of the yarns is a complicated task. At the present time the model is not perfect as it does not guarantee the constant area of the cross-sections of the yarns and is not based on direct physical measurements. The extended approach used in the future implementation complements the model with the force-based calculation procedure of the cross-sectional deformation of a yarn. The spring system representing the ductility of the cross-section is introduced in Figure11. Springs are stretched or compressed depending upon the forces acting on them. The force acting on the *i-th* spring is found by

$$\mathbf{F}_i = k_i\left(\mathbf{u}_i^2 - \mathbf{u}_i^1\right) \tag{7}$$

where k – elastic constant of a spring; $\mathbf{u}$ – shift of a node; superscript indicates the local numbers of a spring; we assume that all first nodes lie on the axis line, all second nodes on the ellipse.



a) 2D view



b) 3D view

Figure 11. Physicality of the cross-section of a yarn

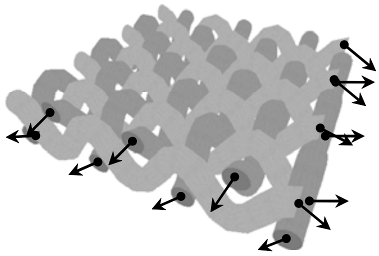
To ensure the constant cross-sectional area of the yarns, we separate the cross-sectional deformation into horizontal and vertical directions, thus dividing the bounding box into 4 quarters (Figure11a). During the side-by-side collision between two OBBs the actual colliding sides have to be detected. When analyzing the collision along the vertical direction, displacements and forces of circumferential nodes acting on the corresponding quarter of the CP should be found. The displacements of the nodes are obtained by comparing coordinates at the current time instant t_i and the previous time instant t_{i-1}, acting forces of the CPs by equation (7). For e.g., if cross-sectional shape of the contacting yarns is vertically squeezing, then we assume that cross-sectional shape of them have to stretch in horizontal direction (Figure11a). The idea is to apply the proportional forces to the CPs composing perpendicular quarters in order to maintain the same cross-sectional area during the deformation of the yarn. After the forces are applied for the CPs from perpendicular quarters, the new shifts of the outside nodes are obtained thus formatting the new cross-sectional shape of the yarns.

6. Results

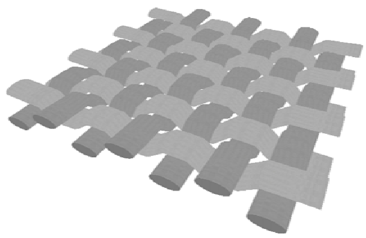
Two models are presented in this paper: obtaining the initial weave by performing tension of the yarns and the shooting-through the fabric test failure modelling. The implementation was performed in C#, and OpenGL was used for visualization.

6.1. Obtaining the initial fabric structure

The initial model of a fabric is obtained by generating the geometrical model describing the weave and further the physical model based on CPs is implemented. We obtain a piece of fabric as a structure of free crimped yarns (Figure 12a). In order to obtain a "woven" state of a fabric the initial tension is performed.



a) Directions of initial velocities



b) tensioned yarns

Figure 12. The fragment of the fabric

The implementation is based on using a system of non-volumetric structural elements as described in Section 3. Boundary nodes of a fabric are affected by the velocities and move as being straightened toward pulling load direction thus obtaining pre-tensioned system of the yarns imitating the fabric weave (Figure 12b). During the movement of the yarns internal collisions at intersections of the yarns occur. To ensure proper simulation, we divide collision handling into two steps: collision detection and response. The SAT algorithm for collision detection and IM for collision response are employed. Both algorithms work in a 3D space by treating yarns as volumetric entities.

When a part of a fabric is tensioned the replication algorithm for obtaining extension of a fabric is applied. We assume that such a piece of a fabric completely repeats the geometrical features of the whole fabric and enables to significantly reduce the computation time. Simulation execution time directly depends on the size of tensioned fabric, besides partially depends on the elasticity modulus of the material, initially applied velocities' magnitude and selected integration time step.

6.2. Penetration of the rigid body through the fabric

The model is intended to explore the properties of the fabric during the ballistic impact. At the initial stage we use the obtained pre-tensioned fabric model by assuming that boundary nodes of yarns are fixed at the ends. The rigid body imitates a bullet being shot against the fabric with 200 m/s initial velocity. The rigid body is visualized as a cone while in implementation of contact handling it is bounded by an OBB and is treated as a cube. In addition, during the contact handling extra collision detection with an external object is performed. The establishment of the breaking condition of a yarn plays an important role in the failure response of the fabric. Here we assume that a yarn breaks at the element where the defined failure threshold is reached. Such an element is eliminated from the structure. In the example the longitudinal deformation threshold is assumed to be 5%. The view of the failed piece of the fabric is presented in Figure13.

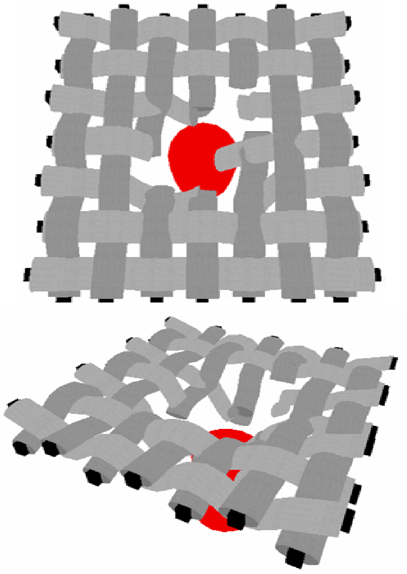


Figure 13. Penetration of a rigid body through the fabric

6.3. Future improvements

The primary work will be focused on the improvements of the existing algorithms. It will cover improvements, which should be made in collision handling among multiple yarns, also between yarns and a rigid body.

The key idea, which will be implemented, is the use of the hierarchical order OBB tree essentially providing a multistage representation of the objects. The box will be built in such a manner that it will enclose the cross-section of the yarn as tightly as possible. The root of such a tree will correspond to an approximation of a yarn by a single OBB. The boxes corresponding to the middle levels of the tree will represent smaller pieces of the yarn, thus providing a somewhat better approximation than the root. The leaf nodes of the tree will represent the actual geometry of the yarn elements. The computational goal of the tree is to minimize the time spent for determining the intersections between the objects.

7. Conclusions

A new approach for modeling the dynamic behavior of woven structures has been presented. The yarns are modeled as chains of springs and simultaneously their full 3D geometry is considered while determining inter-element collision detection and response. An empiric model has been proposed for evaluating deformations of cross-sections of the yarns based on the assumption that the cross section is always elliptic with changing axes of the ellipse. The advantage in comparison with traditional models presenting a yarn as a full volumetric deformable body is the significantly reduced number of degrees of freedom of the structure while preserving the "volumetric" behavior. Numerical examples considering the generation of the initial woven structure by tension of the crimped yarn structure and the failure at shooting-through the fabric demonstrate the good performance of the approach. However, future work is necessary in order to improve and validate the model of the cross-sectional deformations of the yarns.

References

[1] **M. Baker.** Euclidean Space. *http://www.euclideanspace.com*, 2005.

[2] **D. Baraff.** Analytical Methods for Dynamic Simu-lation of Non-penetrating Rigid Bodies. SIGGRAPH'89, *Computer Graphics, Vol.*23, *No.*3, July 1989, 223-232.

[3] **D. Eberly.** Intersection of Convex Objects: The Method of Separating Axes. Geometric tools. *http://www.geometrictools.com*, 2003.

[4] **D. Eberly.** Dynamic Collision Detection using Oriented Bounding Boxes. Geometric tools. *http://www.geometrictools.com,* 2002.

[5] **S. Gottschalk, M. Lin, D. Manocha.** OBBTree: A Hierarchical Structure for Rapid Interference Detection. *Proceedings of ACM Siggraph*, 1996, 171–180.

[6] **Ch. Hecker.** Behind the Screen. *Game Developer Magazine, March*, 1997.

[7] **O. Rebellion.** Olivier's code junkyard. *http://uk.geocities.com/olivier_rebellion,* 2005.

[8] **G. Zhou, X. Sun, Y. Wang.** Multi-chain digital element analysis in textile mechanics. *Journal of Composites Science and Technology* 64, 2004, 239-244.

[9] **Y. Q. Wang, X. K. Sun.** Digital element simulation of textile processes. *Journal of Composites Science and Technology*, 63, 2001, 311-319.

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