ISBN-978-989-9121-13-3
ISTANBUL 22nd International Conference on "Innovations in Science, Engineering & Technology" (ICISET-22)
Nov. 23-25, 2022 Istanbul (Turkey)

Numerical Comparison of Contact Detection Algorithm Adapting for Orthogonal Cutting Process

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Abstract: *The aim of this study is to compare two strategies of contact detection algorithm using master-slave approach and node-to-segment (NTS) discretization for 2D finite element modelling of the orthogonal cutting operation. Define and discuss the search algorithm, the runtime, stability, and the accuracy of Bucket Sort and All-to-All methods and explain step by step the strategies of locating the contact pairs. In the process, the strategy of the bucket sort detection was modified using mathematical treatment to match with the orthogonal cutting operation. Two examples were performed to capture well the effect of nodes and tool moving on the contact detection algorithms considered in the present study. Results show that the bucket sort method is more fast and accurate especially when there is no contact between the tool and the workpiece. In the interest of reproducibility, the Matlab code is made open-source and can be downloaded from(GitHub Website).*

***Keywords*:** *Contact Detection, Bucket Sort Method, All-to-All Method, Orthogonal Cutting.*

1. Introduction

The mechanics of contact are an important issue for our civilization, we find it in much what science reached today, e.g. car tires, metal forming, assembled pieces in engines and turbines, bearings and gears in mechanical devices and electromechanical contacts and also in biomechanics e.g. teeth and human joints, due to this variety the numerical treatment of contact problem by analytical and numerical methods becomes one of the important priorities in many engineering branches today. Contact problems in numerical methods of deformable solids occurs at the interface between two separate bodies. And the contact constraints at this interface cannot be replaced by ordinary boundary conditions imposed on both the contacting surfaces i.e. boundary conditions depend on the strain (Kinematic non-linearity).

Theoretically, there is contact when the metal contact node is on the tool segment. Practically in numerical methods the contact node penetrates the tool segment to a certain depth measured along the normal projection node-segment called the penetration depth or the normal gap (see Fig.01). If penetration detected the impenetrability condition violated and the contact force calculated using one of the methods mentioned in the fifth step Fig.02, the contact forces applying to reposition the contact node on the surface of the penetrated tool i.e. the penetration is completely eliminated.

Numerical simulation of contact problems has been done by many studies in particular the impact phenomenon [1, 2], metal forming [3, 4] and contact in composite materials [13, 14].Contact problem has many important aspects to focus on (see Fig. 02), but contact detection remains the major crucial points and computational costs of contact problem steps because the contact geometry changes significantly through computation and the search algorithm required almost at each time step in FE analysis. Therefore, the search for fast and accurate contact detection algorithm is an absolute necessity for a robust and fast FE analysis, especially for large and

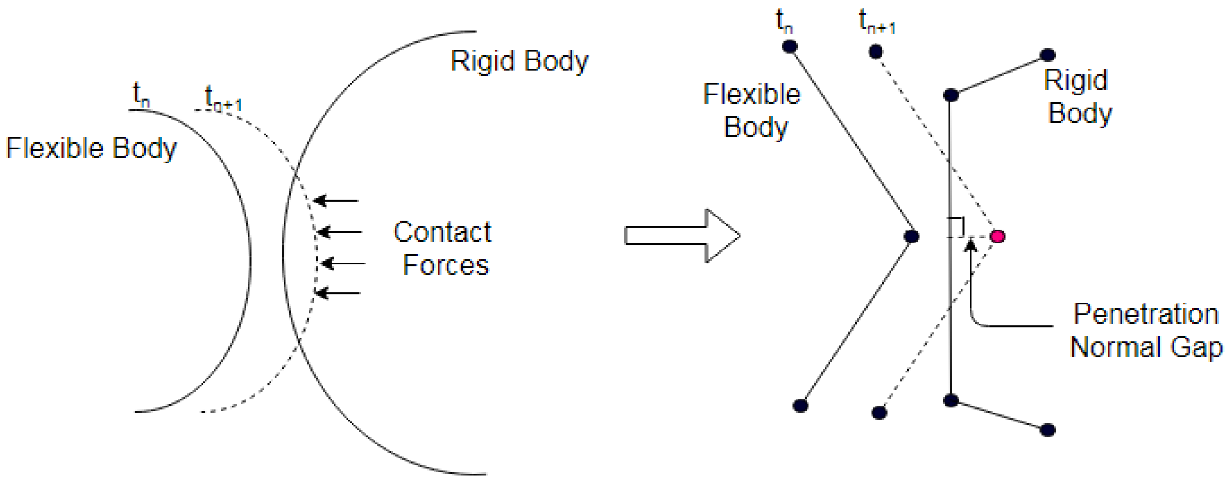

Fig. 1: Continuum & discrete contact problem

multi-contact problems. Several methods proposed in literature, such as Pinball Algorithm proposed by

Belytschko et al. [05, 06], QuickTrace search algorithm By Bruneel et al. [07], a MeshFree contact-detection algorithm By Li, Shaofan et al. [08], Shortest link method by Nezami, Erfan, et al. [12], bounding box algorithms by Malone et al [09, 10] and Attaway et al. [11], which are developed for parallel computation. Most of them are based on subdividing the simulation space and reducing the number of searching for nearest neighbor's elements by distributing them into a regular cell grid and look for neighbors in spatially close cells, but these algorithms are complicated in implementation because they are involved with multiple vector operation and multiple conditional statements.

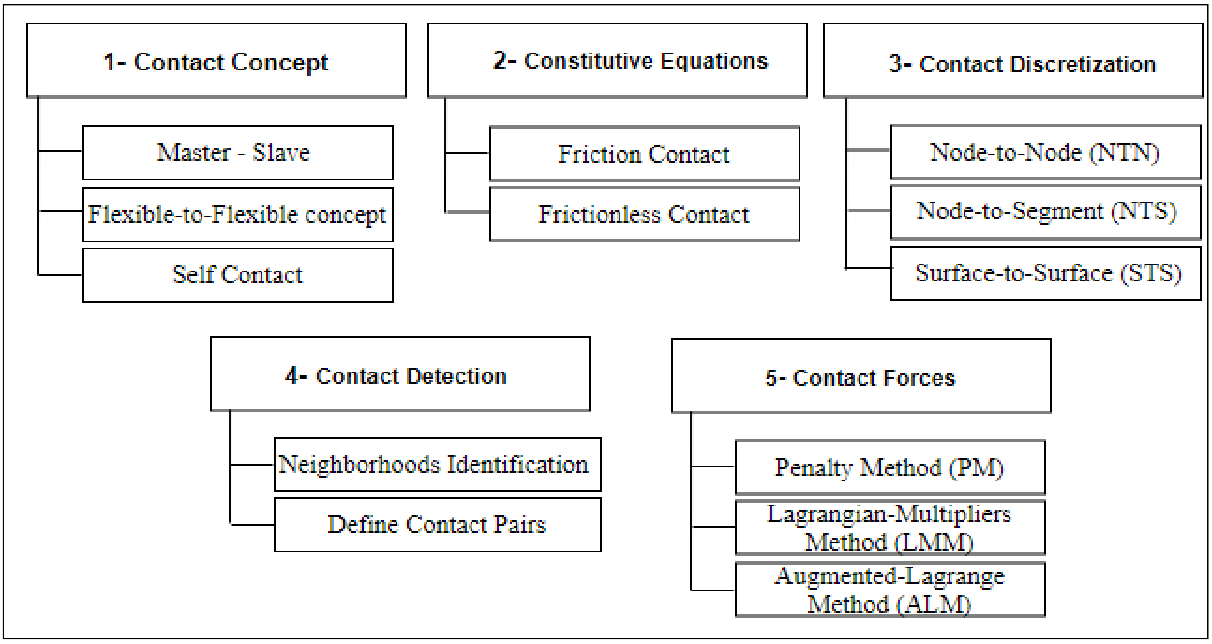

Fig. 2: Summary of Important Steps in Contact Problem Analysis (Implementation)

2. Bucket Sort Method:

Bucket sort algorithm has not a unique meaning, but it always means that a box around a point of the master or slave surface plays an important role. Bucket sort algorithm proposed by [15] a fast and robust detection algorithm based on a rigorous formulation, here we adapt the Bucket sort method for orthogonal cutting process to preserve both the accuracy and the simplicity of the algorithm as in [15], Bucket sort algorithm characterized by two phases:

2.1 Preliminary Phase

- Evaluate the optimal dimensions of the Bucket (D_{max}), Fig. (03) shows the normal and tangential tool displacement in 2D case (rigid tool), the max displacement is the detection parameter D_{max} that should be recomputed at each remeshing or at each n^{th} time step.

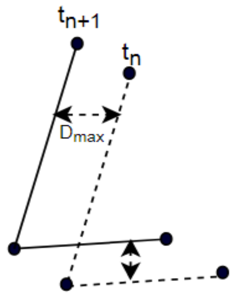

Fig. 3: Illustration of Dmax

- Construct two independent Bounding Boxes containing all material and tool nodes:

$$\min(X_{m,t}^{bb}) = \min(X_{m,t}) - D_{max} \qquad \max(X_{m,t}^{bb}) = \max(X_{m,t}) + D_{max}$$
$$\min(Y_{m,t}^{bb}) = \min(Y_{m,t}) - D_{max} \; \max(Y_{m,t}^{bb}) = \max(Y_{m,t}) + D_{max}$$

Where $X_{m,t}^{bb}$,$Y_{m,t}^{bb}$: Coordinate of the bounding box of the material and the tool.

$X_{m,t}$,$Y_{m,t}$: Coordinate of the material and the tool. (See Fig. 04).

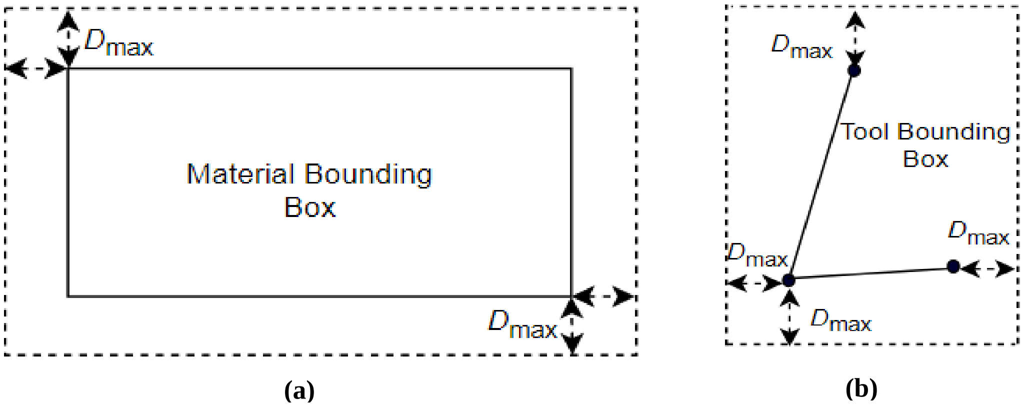

Fig. 4:Illustration of bounding boxes for: (a) Material, (b) Tool

- Potential contact area is determined by the intersection of material and tool bounding boxes $BB = B_m \cap B_t$, verification of the presence of material nodes inside the overlap bounding box. And finally all slave nodes situated in the detection area are checked for the closest master segment for possible penetration (See Fig 05).

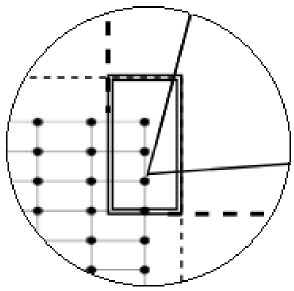

Fig. 5:Illustration the overlap bounding box

2.2. Detection phase:

The detection of the contact pairs are based on:

a) Ensure and increase the accuracy of the algorithm by two steps:
   - Create a bounding box for the node and the segment and check the bounding boxes intersection
   - Project the node on the master segment and check whether the projection is in the valid range or not.

b) The detection strategy: fixe the tool and moves the material same as the linear tool displacement that allows us to create for each node a segment between the previous and the right coordinates then check the intersection of the segment of each node situated on the overlap bounding box against each master segment. It is worth mentioning that this technique is only for node-to-segment discretization.

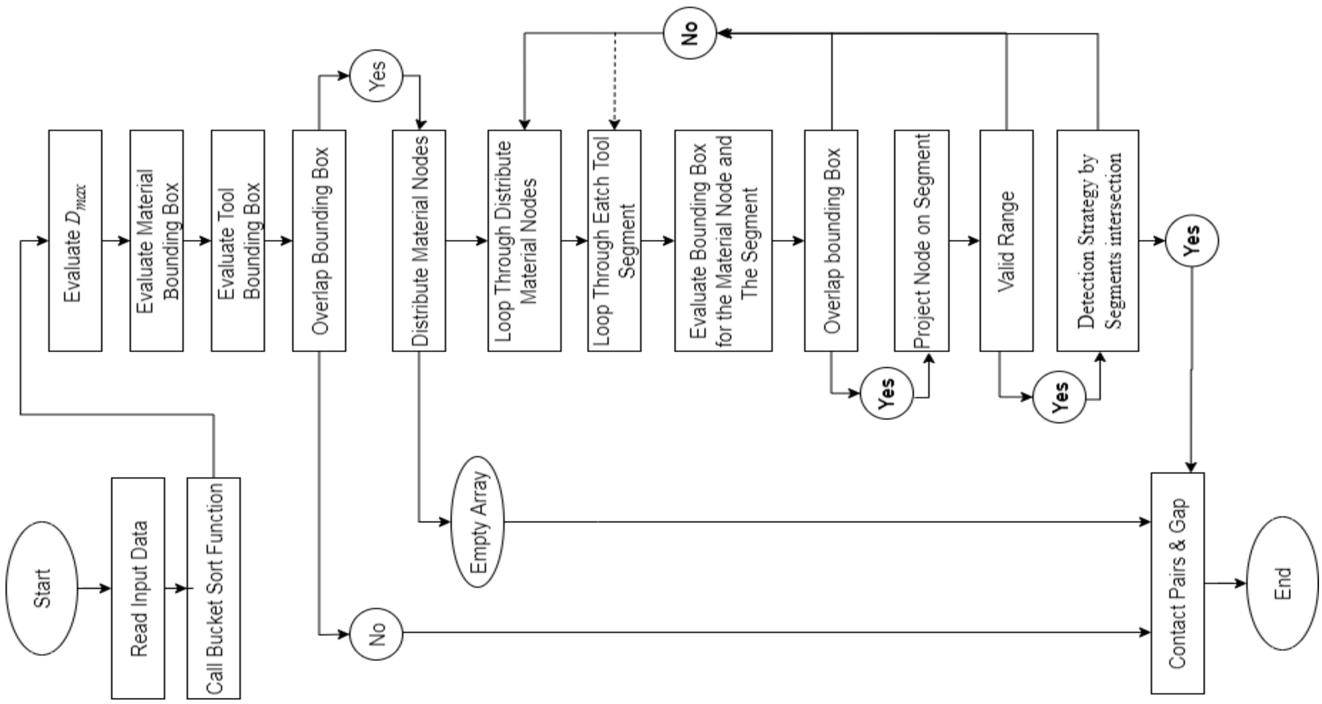

Fig. 6: Flowchart of Bucket Sort Algorithm

3. All-To-All Method:

A simple, efficient and fast enough technique, All-to-All is a classical method based on exhaustive search between all slave nodes of the material and all segments of the tool(s). The exhaustive search between N material nodes and M tool segments requires N*M detection actions, All-to-All is a robust method and acceptable for a moderate number of nodes in contact [15] especially in the case of a small slip when only one execution of the detection procedure is required. It is also worth noting that all-to-all method use the same detection strategy of bucket sort method.

4. Comparisons

In order to compare the runtime of the algorithms two tests were run on 2D orthogonal cutting model shown in Fig. (07) The objective of the two tests is to study the performance of the algorithms with the varying number of contact pairs and nodes. Runtimes are measured and reported in CPU seconds, taken on Intel Core i5-2430M at 2.40 GHz. The first test, focus on the effect of the workpiece refinement on runtime, by fixing the cutting tool in the contact zone and increasing the Nodes from 4 nodes to 82000 nodes. The second test, fixe the workpiece nodes (63000 nodes) and move the tool through the workpiece (10 mm).

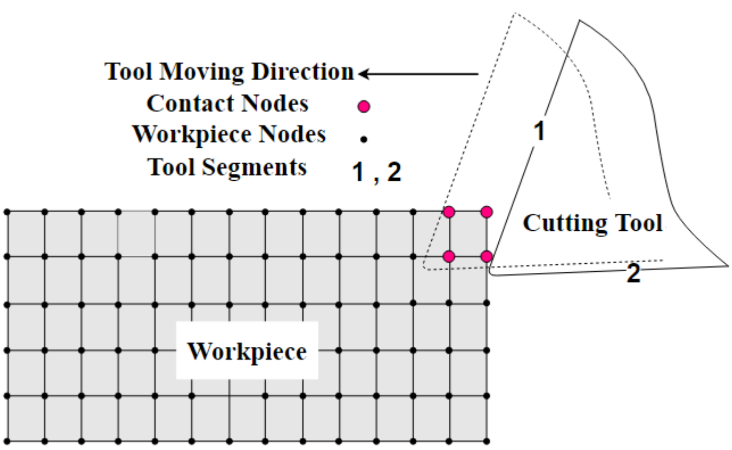

Fig. 7: Simulation set up

Numerical accuracy of the algorithms can be evaluated by comparing the results of the attached Matlab code named “Main Example”, Note that workpiece refinement can be changed for more results to prove the efficiency and robustness of the code with discretization sensitivity of the orthogonal cutting process.

5. Results and Discussion

Contact Detection is a nonlinear process that takes place at every simulation step to detect contact pairs. Therefore, a slight difference in algorithms runtime is more apparent in the overall performance of the FEM simulation especially for the complex geometry and multiple contacts zone that have expensive computationally cost. Fig 08 shows the results of the first test, a large difference in computational time between the two algorithms, appears clearly when increasing nodes. The average time of the bucket sort method is 0.02 Sec while the average time for All-to-All method is 0.64 Sec and this could be explained by the fact that the BS method only performs the operation for the nodes close to the collision zone i.e. nodes situated at the bounding boxes overlap and thereby it decreases the computational time compared to the exhaustive search (All-to-All method) where it performs the operations of the whole nodes against all existing segments and this process can be computationally expensive.

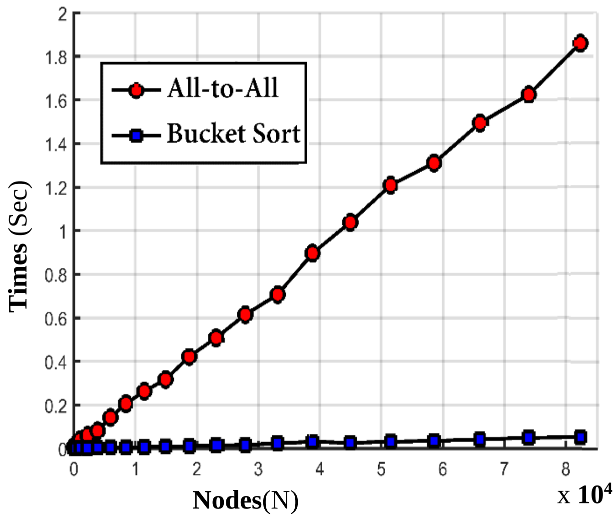

Fig. 8: Runtime of BS and All-to-All Methods According to Increasing Nodes

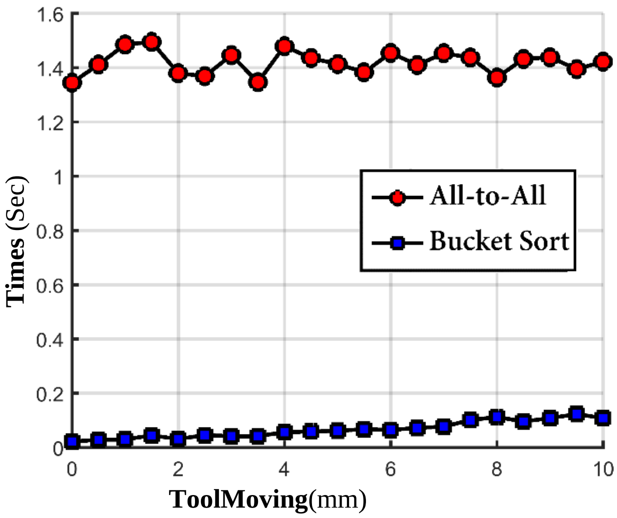

Fig. 9: Runtime of BS and All-to-All Methods According to Tool Moving

Fig 09 shows the second test, Tool progress or the increase of contact pairs has no effect on the runtime of the All-to-All method because workpiece nodes are fixed and the process performs on all nodes, regardless of whether there is a contact or not, while the presence of contact nodes increase the runtime for the BS algorithm because the process depends mainly on the intersection nodes situated on the overlap Bounding Boxes and the contact between the cutting tool segments and workpiece nodes increase the intersection nodes i.e. contact pairs that will be subject to study and thereby increase the time required to extract the contact pairs, but All-to-All method remains incomparable to the runtime required for BS method. Orthogonal cutting process needs a fine mesh i.e. large contact pairs number at the cutting zone to accurately capture the contact forces. Hence, there are no significant differences in static simulation that require few simulation steps between the two search algorithms. These differences begin to appear in dynamic simulation or dynamic refinement in which extremely large simulations should be expected. Therefore to minimize the computational costs neighbour search algorithms e.g. Bucket sort algorithm will be an ideal choice.

6. Conclusion

In this research paper, one of the modern methods used in contact detection was studied compared to a classic method used for simple models [15], the research paper proved that the methods depend on neighbourhood identification (BS method) reduce runtime in a feasible and effective way, especially since the contact problems are based on the iterative and incremental process that could be computationally expensive in particular for complex and irregular geometries, large deformation and large rotation analysis and various contact concept in the same analysis. Thereby this prompts research towards finding new strategies to minimize the computational cost, simplify the contact problem and agree with the analytical and experimental results.

7. References

[1] Kim, Jeong-Hwan, et al. *Numerical simulation of ice impacts on ship hulls in broken ice fields*. Ocean Engineering 180 2019; 162–174.
https://doi.org/10.1016/j.oceaneng.2019.03.043

[2] Moradi, Mostafa, Mohammad Hassan Rahimian, and Seyed Farshid Chini. *Numerical simulation of droplet impact on vibrating low-adhesion surfaces.* Physics of Fluids 32.6 2020; 062110.
https://doi.org/10.1063/5.0012459

[3] Neto, D. M., et al. *Influence of boundary conditions on the prediction of springback and wrinkling in sheet metal forming*. International Journal of Mechanical Sciences 122 2017; 244–254.
https://doi.org/10.1016/j.ijmecsci.2017.01.037

[4] Trzepiecinski, Tomasz, and Hirpa G. Lemu. *Recent developments and trends in the friction testing for conventional sheet metal forming and incremental sheet forming*. Metals 10.1 2020; 47.
https://doi.org/10.3390/met10010047

[5] Belytschko, Ted, and Mark O. *Neal. Contact-impact by the pinball algorithm with penalty and lagrangian methods.* International Journal for Numerical Methods in Engineering 31.3 1991; 547–572.
https://doi.org/10.1002/nme.1620310309

[6] Belytschko, Ted, and I. S. Yeh. *The splitting pinball method for contact-impact problems*. Computer methods in applied mechanics and engineering 105.3 1993; 375–393.
https://doi.org/10.1016/0045-7825(93)90064-5

[7] Bruneel, Herman CJ, and Igor De Rycke. *QuickTrace: a fast algorithm to detect contact.* International journal for numerical methods in engineering 54.2 2002; 299–316.
https://doi.org/10.1002/nme.428

[8] Li, Shaofan, et al. *A meshfree contact-detection algorithm.* Computer methods in applied mechanics and engineering 190.24-25 2001; 3271–3292.
https://doi.org/10.1016/S0045-7825(00)00392-3

[9] Malone, James G., and Nancy L. Johnson. *A parallel finite element contact/impact algorithm for non-linear explicit transient analysis: Part I-The search algorithm and contact mechanics*. International journal for numerical methods in engineering 37.4 1994; 559–590
https://doi.org/10.1002/nme.1620370403

[10] Malone, James G., and Nancy L. Johnson. *A parallel finite element contact/impact algorithm for non-linear explicit transient analysis: Part II Parallel implementation.* International journal for numerical methods in engineering 37.4 1994; 591–603.

[11] Attaway, S. W., et al. *A parallel contact detection algorithm for transient solid dynamics simulations using PRONTO3D.* Computational Mechanics 22.2 1998; 143–159.
https://doi.org/10.1007/s004660050348

[12] G. Nezami, Erfan, et al. *Shortest link method for contact detection in discrete element method*. International Journal for Numerical and Analytical Methods in Geomechanics 30.8 2006; 783–801.
https://doi.org/10.1002/nag.500

[13] Fedulov, Boris N., et al. *Strength analysis and process simulation of subway contact rail support bracket of composite materials.* Applied Composite Materials 23.5 2016; 999–1013.
https://doi.org/10.1007/s10443-016-9495-2

[14] Zhou, Qinghua, et al. *Modeling rolling contact fatigue lives of composite materials based on the dual beam FIB/SEM technique.* International Journal of Fatigue 83 2016; 201–208.
https://doi.org/10.1016/j.ijfatigue.2015.10.014

[15] Yastrebov, Vladislav A. *Numerical methods in contact mechanics*. John Wiley & Sons, 2013
https://doi.org/10.1002/9781118647974