Analysis of the collision-damage susceptibility of sweet cherry related to environment temperature: A numerical simulating method

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Abstract: Sweet cherry is extremely susceptible to collision damage during post-harvest handling which results in increased fruit waste and low fruit economic value. Fruit-to-rigid surface and fruit-to-fruit collision systems were modeled by the dynamic FE method and the sweet cherry model included three parts: exocarp, mesocarp, and pit. A fruit-to-rigid surface horizontal collision testbed was newly developed to validate the prediction accuracy of the fruit FE model. It was found that the fruit model inputting the average elastic moduli and failure stress of the fruit tissues can reproduce the experimental maximum impact force and contact time in the compression stage with the relative error of 1.58 and 1.87 %, respectively. Three mathematical models were proven to be capable of quantitatively assessing the internal damage degree of sweet cherry by three independent variables: collision type, initial fruit velocity, and environment temperature. This study shows an effective numerical simulation approach for objectively predicting the horizontal collision-damage susceptibility of sweet cherry. The principle can be applied to other fruits and thus pave the way for improving tools/equipment and the creation of appropriate conditions for fruit picking, grading, packaging, and transportation to support the actualization of waste reduction and sustainable food systems.

Keywords: Sweet cherry; Collision; Temperature effect; Damage susceptibility; Finite element analysis

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
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<tbody>
<tr>
<td>CT</td>
<td>collision type, $CT = 0$ means fruit-to-rigid surface collision, and $CT = 1$ means fruit-to-fruit collision</td>
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<tr>
<td>$E_{ex}$</td>
<td>elastic modulus of exocarp, MPa</td>
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<tr>
<td>$E_{me}$</td>
<td>elastic modulus of mesocarp, MPa</td>
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<tr>
<td>$E_{p}$</td>
<td>elastic modulus of pit, MPa</td>
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<tr>
<td>$E_{ex}$</td>
<td>tangent modulus of exocarp, MPa</td>
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<tr>
<td>$E_{me}$</td>
<td>tangent modulus of mesocarp, MPa</td>
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<tr>
<td>$F_{max}$</td>
<td>maximum impact force, N</td>
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<tr>
<td>$L_{ex}$</td>
<td>side length of exocarp element, mm</td>
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<tr>
<td>$L_{me}$</td>
<td>side length of mesocarp element, mm</td>
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<tr>
<td>$N_{ex}$</td>
<td>number of failure integration points in all exocarp elements</td>
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<tr>
<td>$N_{me}$</td>
<td>number of failure integration points in all mesocarp elements</td>
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<tr>
<td>$P_{f}$</td>
<td>percentage of damage volume for whole fruit, %</td>
</tr>
<tr>
<td>$P_{ex}$</td>
<td>percentage of exocarp damage volume, %</td>
</tr>
<tr>
<td>$P_{me}$</td>
<td>percentage of mesocarp damage volume, %</td>
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<tr>
<td>$t_0$</td>
<td>time corresponding to start frame, ms</td>
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<tr>
<td>$t_1$</td>
<td>time corresponding to tagged frame, ms</td>
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<tr>
<td>$V_{d}$</td>
<td>fruit damage volume, mm³</td>
</tr>
<tr>
<td>$V_{t}$</td>
<td>fruit geometric volume, mm³</td>
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<tr>
<td>$V_{ex}$</td>
<td>damage volume of exocarp, mm³</td>
</tr>
<tr>
<td>$V_{me}$</td>
<td>damage volume of mesocarp, mm³</td>
</tr>
<tr>
<td>$v$</td>
<td>initial fruit velocity, m/s</td>
</tr>
<tr>
<td>$e_{ex}$</td>
<td>plastic strain of exocarp</td>
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<tr>
<td>$e_{me}$</td>
<td>plastic strain of mesocarp</td>
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<tr>
<td>$\rho_{ex}$</td>
<td>density of exocarp, g/cm³</td>
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<tr>
<td>$\rho_{me}$</td>
<td>density of mesocarp, g/cm³</td>
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<tr>
<td>$\nu_{ex}$</td>
<td>Poisson’s ratio of exocarp</td>
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<tr>
<td>$\nu_{me}$</td>
<td>Poisson’s ratio of mesocarp</td>
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Sweet cherry has a soft texture and is easy to be damaged (Pullanagari and Li, 2021). In the process of picking, sorting, packaging and transportation, there are often collisions between fruit and fruit, and between fruit and rigid surface, resulting in a dynamic mechanical damage which seriously affect fruit economic value (Michailidis et al., 2019; Wang et al., 2020). When sweet cherry is subjected to mechanical impact, the cells in the damaged area were destroyed (Yousefi et al., 2016), and the cell wall was subsequently decomposed under the catalysis of enzymes, causing bruising in the damaged area (An et al., 2022). This bruising causes sweet cherry to become less resistant to microbial invasion, thereby accelerating the decay process, and the loss of their commercial value (Gu et al., 2022). Sweet cherry is always exposed to a wide range of environmental temperatures (approximately 0 to 40 °C) during various post-processing operations (including picking, grading, packaging, transportation, and sales) (Yamazaki and Hosokawa, 2019; Zhao et al., 2021).

From a material mechanics point of view, environmental temperature conditions are one of the environmental factors which have the most influence on the material properties. Different environment temperatures can alter enzymes’ activity, pectin and cellulose viscosity, and water content in pulp cells (Karatas and Arslan, 2016). For example, higher environment temperature can accelerate cellular enzymatic reactions, which is evidenced macroscopically by a reduction in the fruit firmness (Brüggenwirth and Knoche, 2016). Therefore, it is of great significance to study the dynamic impact damage of sweet cherry related to environmental temperature.

Previous studies can be divided into two aspects, namely, the factors affecting the sweet cherry damage source and the effect of low-temperature storage on the changes of nutrient composition and texture of sweet cherry. Brueggenwirth et al. (2014) proposed that the sweet cherry skin was isotropic and its mechanics mainly depended on the epidermis and hypodermis but not the cuticle. Zhou et al. (2016a and 2016b) found that the sweet cherry was more easily damaged at the vibration frequency of 18 Hz when compared to vibration frequencies of 10 Hz and 14 Hz, and the damage rate was as high as 35 %. Alique et al. (2005) investigated the effects of three pretreatment methods of water cooling, natural cooling, and hot water treatment on the texture mechanics of sweet cherry and found that hot water treatment reduced the hardness of sweet cherry from 9.1 ± 0.6 N to 6.2 ± 0.4 N while accelerating the ripening which led to rapid consumption of glucose and malic acid as well as an increase in the fruit softness. Wang and Long (2014) proposed that the firmness of two
sweet cherry varieties increased by 21% ~ 42% after being stored in modified atmosphere packaging at 0 °C for 6 weeks. Brüggenwirth and Knoche (2016) proposed that with the increase in temperature the failure stress and elastic modulus of sweet cherry skins decreased. Zhao et al. (2019) concluded that the storage at near-freezing temperature can effectively delay the ripening process of sweet cherry fruit, evidenced by a prolonged storage time, decrease in the fruit softening rate, and reduction of the decomposition of anthocyanin and sugar content whilst maintaining its skin color.

In summary, the existing literature shows that great progress has been made in characterizing sweet cherry mechanical damage and the texture change in post-harvest at relatively low-temperature storage. Moreover, it is well established that the finite element (FE) method is a powerful numerical prediction technique for solving complex mechanical damage problems of fruit and vegetable subjected to an external force, and has been used as an alternative to providing additional insights that are often impractical or impossible to achieve through real-world experimental or to complement real-world experimentation. For example, researchers have investigated the mechanical damage phenomena of apple (Ahmadi et al., 2016), pear (Salarikia et al., 2017), kiwifruit (Du et al., 2019), grape (Miraei Ashtiani et al., 2019), orange (Namdari Gharaghani et al., 2018) and potato (Nikara et al., 2020) using nonlinear FE method. However, there are few reports about the dynamic impact damage of sweet cherry during postharvest packaging and transportation at different environment temperatures. In consideration that sweet cherry is always exposed to a wide range of environmental temperatures (about 0 to 40 °C) during picking, grading, packaging, transportation, and sales (Yamazaki and Hosokawa, 2019; Zhao et al., 2021), the gap not only limits the prediction of the level of collision damage of the fruit under a specific temperature at post-processing stages, but also hampers theoretical guidance for the development and working environment of sweet cherry picking, grading, packaging and transportation equipment. Sweet cherry fruit has elastic-plastic mechanical characteristics, and its dynamic collision process is an extremely complex nonlinear dynamic behavior (Zulkifli et al., 2020). Compared with the static mechanics process, the dynamic collision is accompanied by a high speed and high energy whilst the action time is short, and the impact force changes rapidly, which results in a large deformation and failure damage in the local fruit tissue participating in dynamic collision at the moment of impact (Celik et al., 2011; Pieczywek and Zdunek, 2014). In the explicit FE method, the central difference integration operator is explicit in that the kinematic state can be advanced using the kinematic parameters (velocity and acceleration) from the previous increment. This method integrates through time by using many small time increments and the use of diagonal element mass matrices improves the computational efficiency of the explicit procedure, thereby making it
suitable for solving the dynamic collision process of sweet cherry (Wu and Gu, 2012). Furthermore, the damage evolution process of the sweet cherry during dynamic collision can be visually studied when the tissue failure stress threshold determined through an experimental process is used for obtaining those parameters such as damage volume and energy change in post-processing analysis, which is difficult to be achieved by real experimental method (Li et al., 2013). Therefore, the purpose of this study was to explore a method that could be used to quantitatively analyze the dynamic collision-damage susceptibility of sweet cherry under different environmental temperatures during postharvest mechanical handlings.

2. Materials and methods

2.1 3D virtual finite element modeling of sweet cherry collision system

Geometric modeling: Firstly, a sweet cherry was cut into two 1/2 bodies along the longitudinal equatorial section with a sharp biological thin cutter, followed by a cut of the seedless 1/2 sweet cherry into 1/4 bodies along the stem-blossom axis (Fig. 1A). A digital camera was used to take pictures of the two cut surfaces on the 1/4 sweet cherry, and then two photos were imported into the front-view reference plane and the right-view reference plane in the sketch drawing area of the SolidWorks software (Version: 2021, Dassault Systemes Simulia Corp., USA), respectively. Subsequently, the boundary contour closed spline on each of the two cut-surface views of the 1/4 sweet cherry was sketched (Fig. 1A) and the 1/4 mesocarp geometric model was created through some operation commands such as filled surface and lofted boss/base. Using the above similar method, the left three blocks of 1/4 mesocarp tissue were geometrically modeled and then all the 1/4 mesocarp geometric models were combined into a single mesocarp geometric model. Similarly, the geometric models of the whole exocarp and pit were created based on the average exocarp thickness of 0.29 mm measured by Han et al. (2022) and the outer contour curve of the pit. Subsequently, a 2D square discrete rigid body (side length: 60 mm) was created in the Abaqus software (Version: 2020, Dassault Systemes Simulia Corp., USA) as the rigid surface for collision, and the exocarp, mesocarp and pit geometric models were imported into the Abaqus for assembling a sweet cheery geometric model (Fig. 1A). Lastly, the geometric models of the fruit-to-rigid surface and fruit-to-fruit collision systems were constructed, respectively.

Interaction definition: For the geometric model of the fruit-to-rigid surface horizontal collision system, the elastic modulus of exocarp was always greater than of mesocarp in sweet cherry (Han et al., 2022). Therefore, when the interaction between exocarp and mesocarp in a real sweet cherry was simulated by the tie constraint, the inner surface of the exocarp model was defined as a master surface while the outer surface of the mesocarp model was defined as a slave surface. Similarly, the outer surface of the pit model was defined
as a master surface while the inner surface of the mesocarp model was defined as a slave surface for simulating the interaction between mesocarp and pit in a real sweet cherry. It is important to ensure that the motion and stress values of common nodes on the master surface and the slave surface of the binding area in a contact pair are the same. The interaction between the sweet cherry and the rigid surface in the fruit-to-rigid surface collision system was defined as general contact (Explicit). In the real world, the physical process of the collision between the fruit and the rigid surface does not produce mutual penetration between the two contact surfaces, so the normal behavior of the contact property was defined as hard contact, and the general contact algorithm prevents contact penetration of nodes on the fruit model surface into the rigid surface by generating contact forces. The tangential behavior was set to obey Coulomb's friction law, and the penalty function friction formula was used to simulate the tangential friction behavior between the fruit surface and rigid surface. A similar approach defines generic contact interactions among the components of the geometric model of the fruit-to-fruit horizontal collision system.

**Boundary conditions and meshing**: For the geometric model of the fruit-to-rigid surface horizontal collision system, the rigid surface was relatively stationary during the collision process, so the rigid surface was fixed to remove all degrees of freedom. For the geometric model of the fruit-to-fruit horizontal collision system, the two fruits move towards each other during the collision process, thus, no boundary conditions were set for the two fruits. It is very important to select appropriate elements for the finite element model, which directly affects the accuracy and duration of finite element calculations. The second-order tetrahedral elements were used for this simulation, which can easily realize the local element refinement of the model, as well as conveniently capture the position of high stress gradient and reduce the complex meshing process whilst being suitable for irregular fruit tissue model (Miraei Ashtiani et al., 2019). Considering that the mesh density will influence the solution accuracy and computer time (Celik et al., 2017), some simple simulations with several element sizes (e.g., 0.8, 1 and 1.5 mm) were performed for the mesh sensitivity check. Hence, the exocarp, mesocarp, and pit model were meshed into 10-node modified quadratic tetrahedral elements (C3D10M) with the global size of 1 mm, and then the exocarp, mesocarp, and pit were meshed into 30230, 85641 and 8533 elements, respectively. The rigid surface was meshed into 3600 elements using R3D4 discrete rigid body elements. Finally, a fruit-to-rigid surface horizontal collision finite element model and a fruit-to-fruit horizontal collision finite element model were created, as shown in Fig. 1B.

**Assumption**: In order to simplify the collision calculation problem of this dynamic finite element model, the simulation process follows the following assumptions: (1) The exocarp and mesocarp tissues of sweet
cherry were regarded as isotropic and homogeneous elastic-plastic biomaterials whereas the pit was considered as a linear elastic material. In this study, the bilinear isotropic hardening model was used as the constitutive model of the elastic-plastic exocarp and mesocarp tissue material, which followed the isotropic hardening law. When the tissue material exceeds its failure stress, plastic deformation occurs, and the stress of the tissue material is a function of its plastic strain. In addition, since the elastic modulus of the sweet cherry pit is much larger than that of the exocarp and the mesocarp, almost no deformation occurs during the collision process, thus the pit was set as a linear elastic material model. (2) The biological yield point of the sweet cherry tissue specimen is regarded as the initial point of tissue plastic failure. At the beginning of loading, the tissue material exhibits linear elastic behavior, and as the load increases to the initial point of tissue plastic failure, the relationship between the stress and strain of the tissue material exhibits a plastic deformation process. At this point, the tissue material begins to produce permanent deformation, and after unloading, the tissue material cannot return to its original state. Therefore, the biological yield point of the sweet cherry tissue was defined as the initial point of plastic failure, and was used to determine whether the sweet cherry tissue will suffer impact damage during a horizontal collision (Celik, 2017). (3) The damage behavior of sweet cherry tissue was predicted by Von mises stress failure criterion (Miraei Ashtiani et al., 2019). The Von mises equivalent stress follows the maximum distortion-energy theory of material mechanics. In biomechanical calculations, it is feasible to use the measured tissue material parameters to calculate the von mises stress distribution inside the tissue for predicting the tissue damage behavior.

2.2 Validation of the fruit finite element model

In order to select the most accurate 3D sweet cherry FE model for the following horizontal-collision simulation and damage prediction analysis, a horizontal collision experiment between sweet cherry fruit and rigid surface was performed at room temperature, and then the minimum, average and maximum elastic modulus and failure stress of the fruit exocarp and mesocarp were inputted into the above established sweet cherry FE model for simulating the real horizontal collision experiment, respectively. Lastly, the results of the experiment and the simulation (Fig. 1C), such as the maximum impact force during the fruit collision process and the contact time during the compression stage (Fig. 1D), were compared.

Experimental method for horizontal collision between sweet cherry fruit and rigid surface: Firstly, a fruit-to-rigid surface horizontal collision test device (Fig. 2A) was self-developed. This is mainly composed of an ejection device, a high-speed camera system, a force data acquisition system and a power supply system. The ejection device has an ejection rod, an ejection tube, a pushbutton, an ejection mouth, a rigid pad, a spring and
a support base. The high-speed camera system includes a high-speed camera (DSC-RX100M4, Sony China Co., Ltd., China) and a camera mount. The force data acquisition system includes a rigid surface, a base, a translation platform, a ruler, a force sensor (JHBM-H1, Bengbu Sensor System Engineering Co., Ltd., China), an amplifier, a data acquisition card (USB3100N, Beijing Art Technology Development Co., Ltd., China) and a computer. The amplifier, the data acquisition card, and the transformer are integrated into the control box. A USB data cable was used to connect the data acquisition card to the computer for the acquisition of force-time data during the horizontal collision between the sweet cherry fruit and the rigid surface. Note that the force sensor should be calibrated to determine a linear function of force and voltage signal before using the device.

Secondly, during the experiment, the ejection rod was pulled backward to make the pushbutton embedded in the slot of the ejection rod. At this time, the spring inside the ejection tube was in a compressed state. The cylinder at the rear end of the rigid pad was installed into the end of the ejection tube. Make sure that the flower stem axis of sweet cherry in the ejection mouth coincides with the axis of the ejection rod and the rigid pad, keeping it perpendicular to the rigid surface. The camera position was adjusted so that the lens was 20 cm above the line between the ejection mouth and the rigid surface. The focal length of the camera was adjusted to ensure that the field of view was large enough and the scale of the ruler was clear. The camera was set to high frame rate (HFR) mode (capture rate is 1000 frames/second). After pressing the camera record button, the computer operated to start recording the force sensor data, then the pushbutton was pulled quickly and the ejection rod in the ejection device impacted the ejection pad forward, then the ejection pad impacted the sweet cherry fruit. Finally, the obtained impact energy of sweet cherry was converted into kinetic energy and the sweet cherry moved horizontally, collided with the rigid surface installed on the force sensor. The force sensor recorded the impact force-time data between the fruit and the rigid surface in real-time during the collision process and transmitted it to the computer through the amplifier and USB3100N data acquisition card for storage. The whole process of the horizontal collision between the sweet cherry fruit and the rigid surface was also recorded synchronously in real-time by a high-speed camera (Fig. 2B). The horizontal collision process between the sweet cherry fruit and the rigid surface includes the compression and recovery stages. After the real experiment in this section, the maximum impact force and the contact time in the compression stage were extracted.

In addition, in order to obtain the fruit initial velocity $v$ during the horizontal collision between the sweet cherry fruit and the rigid surface, the Adobe After Effects software (Version: 2020, Adobe Systems Incorporated, USA) was used to process the sweet cherry motion video captured by the high-speed camera.
The video frame at the ejection mouth was recorded as the start frame, and the corresponding moment is recorded as \( t_0 \); the 20\(^{th} \) frame after the start frame was recorded as the marked frame extracted during the horizontal movement of the sweet cherry with corresponding time was recorded as \( t_1 \). This period of time was denoted as \( \Delta T = t_1 - t_0 \), and the horizontal movement displacement of the sweet cherry during this period is denoted as \( S_f \). Therefore, the average horizontal movement velocity of sweet cherry can be calculated by

\[
v = \frac{S_f}{t_1 - t_0}
\]  

(1)

Simulation method of horizontal collision between sweet cherry fruit and rigid surface: According to the FE model of the 3D collision system created in Section 2.1, the average velocity of the above seven experiments was set as the initial velocity of sweet cherry during the simulation in this section. The elastic modulus and failure stress of the exocarp and mesocarp of sweet cherry fruit at room temperature (20 °C) were set to the maximum average and minimum values of the measured values reported by Han et al. (2022), respectively. Other parameters of the fruit model were set to the value from the literature (He and Shi, 2009; Du et al., 2019; Mahiuddin et al., 2020) (See Table 1). There were three simulations for the horizontal collision process between the fruit and the rigid surface. Because the fruit material showed a nearly elastic-plastic behavior during testing, the collision process was regarded as an inelastic collision, and the impact process included two stages of compression and recovery (Li et al., 2017). During fruit collision with the rigid surface, the impact force on the rigid surface changed with contact time at the contact point. After the simulation, the internal stress distribution change process of the fruit tissue during the collision process was extracted. The maximum support reaction force subjected by the rigid surface was taken as the maximum impact force \( F_{\text{max}} \) of the fruit impacting on the rigid surface during the collision whereas the time taken by the support reaction force rising from 0 (just contact) to the maximum impact force \( F_{\text{max}} \) was recorded as the contact time in the compression stage \( T_c \).

2.3 Loading and simulation
The most accurate FE model of sweet cherry fruit verified in Section 2.2 was used for this horizontal collision simulation. The collision damage of sweet cherry fruit often occurs in the post-harvest processing process whose environmental temperature often fluctuates between 0 and 40 °C, and collision may occur between the fruit and the rigid surface, and between the fruit and the fruit. The initial velocity of the fruit before impact may be different, depending on the external vibration conditions. Therefore, in this paper three initial fruit velocities (1 m/s, 2 m/s, 3 m/s), three environmental temperatures (5 °C, 20 °C, 40 °C), and two different collision types (fruit-to-rigid surface, fruit-to-fruit) were considered. To compare the collision process of two collision types: fruit-to-rigid surface and fruit-to-fruit, considering that two fruits move toward each other for fruit-to-fruit collision type when they collide with each other and the consistency of the collision velocity between the two objects should be ensured for two collision types, so the initial velocity of fruit in the fruit-to-fruit collision type was set to its half in the fruit-to-rigid surface collision type.

During the simulation, the mechanical parameters of the exocarp and mesocarp tissue at the corresponding temperature were input into the FE model to replace the effect of different temperature fluctuations in Table 1 (Han et al., 2022). The Poisson's ratio of sweet cherry exocarp and mesocarp was set based on the existing literature of Mahiuddin et al. (2020). An automatic density measuring instrument (MH-300A, Xiamen Fubusi Testing Equipment Co., Ltd., China) was used to measure the density of sweet cherry exocarp, mesocarp and pit; with reference to the mechanics of walnut shells (He and Shi, 2009) as these parameters were used to set the elastic modulus and Poisson's ratio of sweet cherry pit. The horizontal collision process of sweet cherry was accompanied by its own large deformation, so a large-displacement formulation was considered here when setting the collision analysis step in the simulation model. The duration of each collision was set to 10 ms, and the simulation analysis process was set to 100 analysis steps. Based on the selected high-accuracy sweet cherry horizontal collision FE model in Section 2.2, 18 horizontal collision FE simulations (3 temperature levels × 2 collision types × 3 velocity levels) in Abaqus/explicit were performed based on an HP Z840 High-Performance Computer Platform with two E - 2683V4 16 - core 2.1 GHz Intel(R) CPUs and a 160 G DDR4 - 2133 RegRAM. The detailed mechanical parameter setting in each simulation is shown in Table 1.

2.4 Post-processing analysis

After the simulations were completed, the maximum Von mises stress, maximum impact force $F_{\text{max}}$, and collision damage volume of the fruit tissue during the collision process under different parameter conditions (environment temperature, initial velocity, collision type) were extracted from the output results. The collision damage volume was assessed via the approach described hereafter, which is similar to An et al. (2022). For the
sweet cherry collision simulation process, the stress change process of the integration points in the tissue element was stored in the ODB file. A “Damage Analysis” post-processing plug-in in the Abaqus software was secondary developed using Python language to access and read the stress changes of all the element integration points of the exocarp and mesocarp tissue FE model during the entire collision simulation process. All the elements of the fruit FE model were C3D10M with four integration points. Assuming that all elements were regular tetrahedrons, and each integration point represents 1/4 of the volume of the entire tetrahedron. When the stress value of an integration point in a tissue element was greater than the failure stress of the tissue, the integration point was regarded as a failure integration point, and the failure volume of this element was 1/4 of the whole element volume. After each collision simulation was completed, the Damage Analysis post-processing plug-in was used to calculate the total number of failure integration points in the exocarp and mesocarp model, respectively; and the SolidWorks software was used to extract the geometry model volume of exocarp, mesocarp and pit, respectively. The sum of these three parts’ volumes was recorded as the total fruit volume \( V_f \). Equations (2) and (3) were used to calculate the damage volume of the exocarp and mesocarp after each collision simulation, respectively. Equations (4) and (5) were used to calculate the percentage of the damage volume of the exocarp and mesocarp, respectively.

\[
V_{ex} = \frac{1}{4} \times N_{ex} \times \frac{\sqrt{3}}{12} L_{ex}^3
\]  
(2)

\[
V_{me} = \frac{1}{4} \times N_{me} \times \frac{\sqrt{3}}{12} L_{me}^3
\]  
(3)

\[
P_{ex} = \frac{V_{ex}}{V_f} \times 100\%
\]  
(4)

\[
P_{me} = \frac{V_{me}}{V_f} \times 100\%
\]  
(5)

2.5 Statistical analysis

The multiple linear regression analysis was performed using SAS version 9.2 software (SAS Institute Inc., Cary, NC, USA), and the significance level was set at 0.05 (\( p = 0.05 \)). The maximum impact force, the fruit damage volume and the percentage of damage volume were used as the collision damage degree indicators for evaluating the susceptibility to collision damage of the sweet cherry fruit and were set as dependent variables. Their potential influence factors, such as environment temperature, initial fruit velocity, and collision type, were defined as independent variables. The collision type was a dummy variable, and its two levels, "fruit-to-rigid surface collision type" and "fruit-to-fruit collision type" were coded as "0" and "1", respectively. The environment temperature and the initial fruit velocity were quantitative variables.

3. Results and discussion
3.1. Validation of the fruit finite element model

Figure 1C shows the Von mises stress distribution contour of the exocarp, mesocarp and pit on the longitudinal equator section at the moment when the sweet cherry produced the maximum impact force during the horizontally collision with the rigid surface at the fruit initial velocity of 2.7 m/s. In this horizontal collision FE model, the elastic modulus, failure stress, Poisson's ratio and density of the sweet cherry’s exocarp tissue were 2.10 MPa, 0.84 MPa, 0.40 and 1.01 g/cm³, the elastic modulus, failure stress, Poisson's ratio and density of the sweet cherry’s mesocarp tissue were 0.30 MPa, 0.08 MPa, 0.37 and 1.05 g/cm³, and the elastic modulus, Poisson's ratio and density of the pit were 13000 MPa, 0.3 and 0.91 g/cm³, respectively. When the stress value of each tissue element exceeded its failure stress threshold, the element was presented as a gray failure element, that is, a damaged area. When the sweet cherry horizontally collided with the rigid surface at an initial velocity of 2.7 m/s, the maximum Von mises stress of exocarp and mesocarp tissue were 0.269 MPa and 0.313 MPa, respectively. The maximum stress value in exocarp FE model was much smaller than its tissue failure stress value, so the exocarp did not have any obvious damage during the horizontal collision at this velocity. However, the maximum stress value in the mesocarp FE model was greater than its tissue failure stress value, so the mesocarp had obvious damage during the horizontal collision process at this velocity, corresponding to the gray area in the tissue model.

Figure 1D shows the comparison between the simulation and the real experimental results when the sweet cherry horizontally collided with the rigid surface at a velocity of 2.7 m/s. Among them, the simulation 1, simulation 2 and simulation 3, respectively represent the simulation results when the elastic modulus and failure stress of the exocarp and mesocarp took the minimum, average and maximum measured values in the fruit FE model. These result parameters are the maximum impact force $F_{\text{max}}$ of the fruit impacting on the rigid surface and the contact time $T_c$ in the compression phase of the collision process. The experiment result presents the mean ± standard deviation of two experimental result parameters. Compared with the experimental result, the relative errors of the maximum impact force of the fruit impacting on the rigid surface in the three simulation results were 11.3 %, 1.58 % and 4.76 %, and the relative errors of the contact time in the compression phase of the collision process were 3.04 %, 1.87 %, and 6.78 %, respectively. Therefore, when each tissue mechanical parameter took the average value in the fruit FE model, the relative error between the simulation and real experimental result was the smallest, and this fruit model would have a high prediction accuracy for dynamic collision behavior, so it would be used in the following sweet cherry collision damage analysis.
3.2 Damage evolution during the fruit-to-rigid surface and fruit-to-fruit collision processes

Figure 3-A1 and A2 show the Von mises stress distribution contour and the velocity distribution contour of the fruit in five motion states (0th, 15th, 30th, 45th, and 100th steps) in the fruit-to-rigid surface collision system ($T = 20^\circ C, v = 2\ m/s$), respectively. The 0th step is the initial state of the sweet cherry moving horizontally to the rigid surface at an initial velocity of 2 m/s. The 15th step represents a certain motion state of the sweet cherry in the compression phase of the collision process. At this step when the kinetic energy of the fruit was reduced, the kinetic energy was converted into the deformation energy inside the fruit, and the horizontal moving velocity of the sweet cherry acting on the rigid surface continued to decrease. The 30th step represents the moving state of the sweet cherry was at the maximum deformation, and the maximum contact stress occurred inside the fruit. The 45th step represents a certain motion state of the sweet cherry in the recovery phase of the collision process, the elastic deformation energy was converted into the kinetic energy of the fruit, and the horizontal moving velocity of the fruit was toward the left and continued to increase. The 100th step represents the motion state of the sweet cherry at 10 ms. Figures 3-A3, A4 and A5 show the Von mises stress distribution contour of the exocarp, mesocarp and pit on the fruit longitudinal equator section during the fruit-to-rigid surface collision process, respectively. Similarly, Figures 3-B1 and B2 show the Von mises stress distribution contour and the velocity distribution contour of the sweet cherry in five motion states (0th, 17th, 34th, 51st, and 100th steps) in the fruit-to-fruit horizontal collision system ($T = 20^\circ C, v = 1\ m/s$). In the fruit-to-fruit horizontal collision system, the sweet cherry fruit showed a similar motion state and energy conversion process to the fruit-to-rigid surface horizontal collision system at each step. The maximum Von mises stresses of the exocarp, mesocarp, and pit in the fruit-to-rigid surface collision process were larger than those in the fruit-to-fruit collision process (Fig. 3-A3, A4 and A5 and Fig. 3-B3, B4 and B5), and the damage area on the mesocarp model of the fruit-to-rigid surface collision process was larger than that of the fruit-to-fruit collision process (Fig. 3-A4 and Fig. 3-B4). This is due to the hardness difference between the two collision targets. The gray area in Fig. 3A and Fig. 3B represents the damaged area of the fruit. When the initial velocity of the fruit increased from 1 to 3 m/s and the environment temperature increased from 5 °C to 40 °C, no impact damage occurred in the sweet cherry exocarp, and the damage mainly occurred in the fruit mesocarp. This may be due to the fact that the exocarp tissue cells are small, dense, and have high toughness, which is difficult to be damaged during mild collision.

Figure 4A shows the internal damage evolution of fruit in the fruit-to-rigid surface horizontal collision process ($v = 2\ m/s$). Obviously, the damage did not occur instantaneously when the collision began but rather
after a certain time as the contact time increased. When the internal stress of the fruit accumulated to a certain level (that is, the failure stress of the tissue), the damage began to appear and continued to increase. According to the damage evolution curve (damage volume vs contact time), the impact damage volume of the fruit showed a nonlinear increase trend with the increase in the contact time, and in the later compression phase, the impact damage growth gradually slowed down, which may be related to the changing energy in the collision process. Studies have shown that internal damage of fruit is closely related to the absorption energy (An et al., 2020). According to the ALLKE curve of fruit kinetic energy vs contact time in the post-processing results, in the later compression phase, the rate of the reduction of the kinetic energy of the sweet cherry became slow, and the kinetic energy was mainly transferred into the internal deformation energy of the sweet cherry; that is, the absorption of energy by the fruit also led to the change of the internal stress of the fruit and caused the damage of the fruit tissue. The maximum damage volumes of sweet cherry in the fruit-to-rigid surface collision process at 5 °C, 20 °C and 40 °C were 115.79 mm\(^3\), 222.30 mm\(^3\) and 328.83 mm\(^3\), respectively. Therefore, under the same initial fruit velocity, the impact damage degree of the sweet cherry increased with increasing temperature. Figure 4B shows the internal damage evolution of the sweet cherry in the fruit-to-fruit collision process. The trend of the internal damage evolution of the sweet cherry under the two collision types was basically similar, while their damage degree shows an obvious difference. The maximum impact damage volumes of sweet cherry in the fruit-to-fruit collision process at 5 °C, 20 °C and 40 °C were 32.70 mm\(^3\), 67.94 mm\(^3\) and 98.67 mm\(^3\), respectively.

3.3 Sensitive of the fruit finite element model

The mechanical parameters of the sweet cherry may affect the maximum impact force and contact time of the fruit acting on the rigid surface during the collision process. Figure 5A shows the impact force - contact time curves of the horizontal collision process between fruit and rigid surface when the elastic modulus and failure stress of the exocarp tissue and mesocarp tissue was average value at 20 °C (\(E_{ex} = 2.09\) MPa, \(\sigma_{ex} = 0.84\) MPa, \(E_{me} = 0.30\) MPa, \(\sigma_{me} = 0.08\) MPa), increased by 20 % (\(E_{ex} = 2.51\) MPa, \(\sigma_{ex} = 1.00\) MPa, \(E_{me} = 0.36\) MPa, \(\sigma_{me} = 0.10\) MPa), and decreased by 20 % (\(E_{ex} = 1.67\) MPa, \(\sigma_{ex} = 0.67\) MPa, \(E_{me} = 0.24\) MPa, \(\sigma_{me} = 0.07\) MPa), and the initial velocity of the fruit was all set to 2 m/s. The horizontal collision process between two objects included two phases: compression and recovery, which is similar to the viewpoint of apple collision proposed by Dintwa et al. (2008). In the compression phase, the impact force between the two objects increased nonlinearly with the increase of the collision contact time, and in the recovery phase, the impact force between the two objects decreased nonlinearly with the increase of the collision contact time. When the elastic-plastic
mechanical parameters of the sweet cherry tissue were inputted by its average values, the maximum impact force and contact time of the fruit acting on the rigid surface were 17.91 N and 5.0 ms, respectively. With the increase in the elastic modulus and failure stress of the sweet cherry tissue, the maximum impact force of the fruit acting on the rigid surface obviously increased while the contact time of the fruit acting on the rigid surface decreased. This result is not in agreement with that of two rigid bodies’ collision. Figure 5B shows the impact force - contact time curves of the horizontal collision process between fruit and rigid surface when the plastic strains of the exocarp and mesocarp were 0.01, 0.02 and 0.03, respectively ($E_{es} = 2.09$ MPa, $\sigma_{es} = 0.84$ MPa, $E_{me} = 0.30$ MPa, $\sigma_{me} = 0.08$ MPa, $v = 2$ m/s). The results showed that the maximum impact force and contact time of the fruit acting on the rigid surface almost did not change with the increase in the plastic strain of the exocarp and mesocarp tissue.

The initial velocity of the fruit obviously affects the maximum impact force and contact time of the fruit acting on the rigid surface. Figure 5C shows the impact force - contact time curves of the horizontal collision process between fruit and rigid surface when the initial velocity of the fruit was 1 m/s, 2 m/s and 3 m/s, respectively. When the initial velocity of the fruit increased from 1 m/s to 3 m/s, the maximum impact force of the fruit acting on the rigid surface increased by 258.2 %, and the contact time decreased by 28.6 %. The curvature radius of the contact point on the fruit surface also affects the maximum impact force and contact time of the fruit acting on the rigid surface. Figure 5D shows the impact force - contact time curves of the horizontal collision process between fruit and rigid surface when the curvature radius of the contact point on the fruit surface was 10.32 mm and 18.28 mm, respectively. When the curvature radius of the contact point on the fruit surface increased from 10.32 mm to 18.28 mm, the maximum impact force of the fruit acting on the rigid surface increased by 8.5 %, and the contact time of the fruit acting on the rigid surface decreased by 4.0 %.

One possible explanation is that with the increase in the curvature radius of the contact point on the fruit surface, the collision area between the fruit and the rigid surface as well as the total force of the fruit tissue element nodes in the collision contact area increased, thereby the maximum impact force of the fruit acting on the rigid surface increased. Once the initial velocity $v$ of the fruit is the same, the collision contact time will decrease under the condition of the conservation of momentum.

### 3.4 Prediction of the collision-damage susceptibility of sweet cherry

The results of the multiple linear regression analysis are listed by three Equations (6 - 8), which predicts the collision-damage susceptibility of the sweet cherry in the horizontal collision process with the maximum Von mises stress of fruit, the fruit damage volume, and the percentage of damage volume as dependent
variables, respectively. The three independent variables, namely collision type, initial fruit velocity, and environmental temperature, had significant effects on three dependent variables ($p < 0.05$). From these regression equations, it can be seen that the collision type has the greatest effect on the damage susceptibility of the sweet cherry, followed by the initial fruit velocity and environmental temperature. The maximum stress, fruit damage volume and percentage of damage volume in the fruit-to-rigid surface collision type were 0.113 MPa, 194.80 mm$^3$ and 1.72 % thus higher than those in the fruit-to-fruit collision type. The collisions between fruit and rigid surface and between fruit and fruit are the common collision type in the fruit postharvest handling. By contrast, it is found that the fruit is more easily damaged when it collides with a rigid surface when compared to the fruit-to-fruit collision at the same environmental temperature and initial fruit velocity. Similar results were reported in the research of the apple collision damage (Ahmadi et al., 2016). Different collision types include some potential hidden basic parameters that affect the degree of fruit collision damage, such as the surface curvature and the natural mechanical properties of the collided object (Yousefi et al., 2016; Zhou et al., 2016b).

Studies with the initial fruit velocity range of 1 m/s ~ 3 m/s, showed that when the initial velocity of sweet cherry increased by 1 m/s, the maximum Von mises stress inside the fruit increased by 0.051 MPa, the fruit damage volume increased by 143.49 mm$^3$ and the percentage of damage volume increased by 1.27 %. The magnitude of the initial velocity of the sweet cherry determines the magnitude of the momentum of the fruit before the horizontal collision to an object. The greater the initial velocity of the fruit, the greater are its momentum, the impulse of the sweet cherry to the collided object in a short time, and the maximum impact force of the fruit during the collision process. These results agree with those of Du et al. (2019) and Zhou et al. (2016b) showing that when the kiwifruit was dropped from the heights of 0.25 m, 0.50 m, and 1.0 m, the maximum stress of fruit was 2.082 MPa, 2.386 MPa, 3.101 MPa, and the fruit damage volume were 1878.4 mm$^3$, 4144.2 mm$^3$, 10564.2 mm$^3$, respectively (Du et al., 2019); and the drop height had a significant effect on the damage volume of sweet cherry (Zhou et al., 2016b). Different drop heights determined that sweet cherry had different initial velocities before the collision, and will produce different impact energies during the collision process. Moreover, there is a positive linear correlation between the fruit damage volume and the impact energy (An et al., 2022). Therefore, it is possible to reduce the collision-damage susceptibility of a fruit by lowering the initial vibration velocity of the fruit during postharvest handling.

In the temperature range of 5 °C ~ 40 °C, when the environmental temperature increased by 1 °C, the maximum Von mises stress inside the fruit during dynamic collision process decreased by 0.001 MPa, the fruit...
damage volume increased by 4.09 mm³, and the percentage of damage volume increased by 0.04 %. The elastic modulus and failure stress of the sweet cherry showed a decreasing trend with the increase in environmental temperature (Han et al., 2022), so this could explain the decrease in the maximum stress of the fruit and the increase in the fruit damage volume and the percentage of damage volume during the horizontal collision of the sweet cherry with the increasing environmental temperature. Therefore, the mechanical properties of fruit biomaterials are also important indicators to judge the collision-damage susceptibility of fruit. Similar results were reported in the impact damage research of kiwifruit (Du et al., 2019).

\[
\sigma_{\text{max}} = -0.113CT - 0.001T + 0.051v + 0.172 \quad R^2 = 0.97 \quad (6)
\]

\[
V_{\text{fd}} = -194.80CT + 4.09T + 143.49v - 113.05 \quad R^2 = 0.78 \quad (7)
\]

\[
P_{\text{fd}} = -1.72CT + 0.04T + 1.27v - 1.00 \quad R^2 = 0.78 \quad (8)
\]

4. Conclusion

A dynamic FE model was developed to quantitatively analyze the dynamic collision-damage susceptibility of sweet cherry under different environmental temperatures relevant to postharvest mechanical handling conditions. Also, a newly designed and built fruit-to-rigid surface horizontal collision testbed was used to experimentally validate the model. The average elastic moduli and failure stress of tissues were verified to be able to reproduce the maximum impact force and contact time in the compression stage of the fruit-to-rigid surface collision experiment. In the fruit-to-rigid surface and fruit-to-fruit collision processes, a nonlinear increasing relationship between fruit damage volume and collision contact time was observed. It was found that the maximum impact force and contact time were mainly sensitive to the elastic moduli and failure stress of tissues, initial fruit velocity, and curvature radius of the contact point at the fruit surface but were not sensitive to the tissue plastic strain during fruit-to-rigid surface collision simulation. Results of the multiple linear regression analysis showed that the collision type was the most important factor affecting the horizontal collision-damage susceptibility of the sweet cherry, followed by the initial fruit velocity and environmental temperature. Three obtained mathematical models can be used as a tool to quantitatively assess the degree of the internal damage of sweet cherry during grading, packaging, and transport for recommending improved handling methods in the supply chain. This study shows an effective numerical simulation approach for objectively predicting the horizontal collision-damage susceptibility of sweet cherry and other fresh fruit.

Acknowledgements

This work was supported by a European Marie Curie International Incoming Fellowship (326847 and 912847), a Chinese Universities Scientific Fund (2452018313) and an International Cooperation Key Plan of
Shaanxi Province (2022KWZ-12).

Author contributions

X.H. designed the experiment, performed simulation and wrote the manuscript. Y.L., F.T., Z.L. and M.K. review and editing the manuscript. Z.L. and B.L. provided the resources support. X.H., Z.L. and B.L. provided calibration data. X.H., Y.L. and Z.L. designed the data visualization.

Declaration of competing interest

The authors declare no competing interest.

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Fig. 1 Finite element modeling and simulation of two collision systems. (A) fruit geometric modeling, (B) finite element modeling of two horizontal collision systems, (C) stress distribution contour of exocarp, mesocarp and pit on the longitudinal equator section of fruit model at the moment of the maximum fruit deformation, (D) the maximum impact force and contact time in collision experiment and simulations, Simulation 1, 2 and 3 refers to the results of three simulations inputted by the minimum, average and maximum measured elastic modulus and failure stress of exocarp and mesocarp, respectively.
Figure 2

Fig. 2 Fruit-to-rigid surface horizontal collision experiment. (A) the fruit-to-rigid surface horizontal collision test device, (B) the moving process of a fruit in the horizontal collision test video.
Figure 3

Two types of horizontal collision processes. (A1, A2) Von mises stress distribution contour and velocity distribution contour of whole fruit in the fruit-to-rigid surface collision process, respectively; (A3, A4, A5) Von mises stress distribution contour of exocarp, mesocarp and pit in the fruit-to-rigid surface collision process, respectively; (B1, B2) Von mises stress distribution contour and velocity distribution contour of whole fruit in the fruit-to-fruit collision process, respectively; (B3, B4, B5) Von mises stress distribution contour of exocarp, mesocarp and pit in the fruit-to-fruit collision process, respectively.
Fig. 4 Damage evolution process of sweet cherry. (A) Damage volume vs Contact time of sweet cherry in the fruit-to-rigid surface collision process ($T$ – environmental temperature), (B) Damage volume vs Contact time of sweet cherry in the fruit-to-fruit collision process.
Fig. 5 Sensitive analysis of the fruit FE model. (A) Sensitive of the fruit FE model to tissue elastic modulus, (B) Sensitive of the fruit FE model to tissue plastic strain, (C) Sensitive of the fruit FE model to initial fruit velocity, (D) Sensitive of the fruit FE model to curvature radius.
Table 1

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<td>3</td>
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<td>(Han et al., 2022)</td>
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