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Research Article

Determining the effect of bird parameters on bird strikes to commercial passenger aircraft using the central composite design method

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ABSTRACT

Today, bird strike is one of the most threatening problems to flight safety. A bird strike damage in flight can result in serious structural damage or even fatal accidents. A bird strike model requires high computational power for model preparation and nonlinear explicit analysis because of composite materials, contact definitions and other complex analysis parameters. Investigating the effects of design parameters on bird strike is a costly and time-consuming practice. The influence of various parameters such as bird velocity and impact angle has been also evaluated on a composite target in this research.
Investigation of the effects of bird parameters on a composite target provides a clearer definition of the strength limits and energy transfer of composite materials exposed to bird strikes. Real bird strike tests are in good agreement with Ls-Dyna analysis results in this study. The unique aspect of this research is that the Central Composite Design (CCD) method, one of the Design of Experiment (DOE) methods, is one of the first applications in the bird strike problem. Bird strike simulations were performed in different analysis parameters based on the Central Composite Design (CCD) method and the effects of the parameters on bird strike were found with the regression equations obtained from Minitab.

Keywords: Bird strike; Central composite design (CCD); Design of experiment (DOE); Impact test; Smoothed particle hydrodynamics (SPH)

1. Introduction

Aircraft collisions with birds and other wildlife have become an increasing concern for aviation safety in recent years. Factors that contribute to this increasing threat are increasing populations of large birds and increased air traffic by quieter, turbofan-powered aircraft. Globally, wildlife strikes destroyed over 263 aircraft (Figure 1) between 1988 and 2018, and even killed more than 282 people [1]. The Federal Aviation Administration (FAA) extendedly compiles a database of all reported wildlife strikes to U.S. civil aircraft and to foreign carriers experiencing strikes in the USA. About 220,000 strike reports have been compiled from 2,050 USA airports and 310 foreign airports for January 1990 through September 2019 (about 16,000 strikes in 2018) [2]. Some of these strikes resulted in fatal accidents. These bird strike examples from the database, presented in chronological order, show the serious impacts that strikes by birds can have on aircraft and demonstrate the widespread and diverse nature of the problem (Table 1) [2].

Fig. 1. Aircraft destroyed due to bird strike [3]

On 7 November 2007, a large blue heron struck the left wing leading edge of the B-737 aircraft, causing damage to the aircraft (Figure 2) [3].

Table 1. Some of the human fatalities and injuries due to bird strikes

Date	Aircraft	People	Damage
19/11/2017	Bell 407	3 deaths	Aircraft destroyed
27/06/2017	Jordan John RV7	2 deaths	Aircraft destroyed
20/04/2016	C-172	4 deaths	Aircraft destroyed
13/02/2013	Avions Fairey Tipsy Nipper	1 deaths	Aircraft destroyed
4/1/2009	Sikorksy S-76C	8 deaths,1 injury	Aircraft destroyed
4/3/2008	Cessna Citation I	5 deaths	Aircraft destroyed
23/10/2007	Piper 44	2 deaths	Aircraft destroyed
8/7/2003	Cessna 172	2 deaths	Wings, engine, (possibly more)
10/5/2003	MD A-4N (former military)	1 deaths	Aircraft destroyed
4/3/1998	Piper 23	2 deaths	Aircraft destroyed
15/07/1994	Cessna 172	1 deaths	Aircraft destroyed
16/05/1994	Bell BHT-47	1 deaths	Aircraft destroyed
5/6/1992	Starduster SA 300	1 deaths	Aircraft destroyed

Fig. 2. Bird strike damage to B737 aircraft left wing leading edge [3]

Fig. 3. Turkish Airlines aircraft in a flock of birds [4]

With the realization of the importance of accidents caused by bird strikes at Turkish Airlines, reporting and research on this issue has gained momentum. Figure 3 shows a situation related to the accidental diving of an aircraft in the Turkish Airlines fleet into a bird flock.

European Aviation Safety Agency (EASA) CS-25.631 and Federal Aviation Administration (FAA) FAR-25.571-e-1 (Bird Strike Damage) requires that the aeroplane must be designed to assure capability of continued safe flight and landing of the aeroplane after impact with a 4 lb bird when the velocity of the aeroplane (relative to the bird along the aeroplane's flight path) is equal to V_C (Design Cruise Speed) at sea-level or 0.85 V_C at 2438 m (8000 feet), whichever is the more critical. Compliance may be shown by analysis only when based on tests carried out on sufficiently representative structures of similar design [5].

It is common practice today to design and test aircraft components as bird proof, redesigning and retesting until the relevant component passes the tests. Bird strike tests with real birds are costly and time consuming, instead finite element analysis methods such as Ls-Dyna are used in recent years, there are many academic studies in this field [6-13]. However, so far, there has been no academic study examining the impact angle and impact velocity effects using the Central Composite Design method. The determination of the extent to which bird velocity and impact angle parameters affect outputs such as deformation, kinetic energy and internal energy with the regression equation is one of the unique aspects of this research.

2. Theoretical Background

The projectile has a hydrodynamic behavior during the impact. Soft body impact will be defined as impact in which the stresses generated substantially exceed the strength of the projectile but are well below the strength of the target material. This implies that soft body projectiles wil1 flow upon impact while the target may see little or no plastic deformation [7].

The bird strike event is often considered as a jet of water hitting a target. It can be divided into two stages: the initial shock and the steady flow. The pressure of the initial shock (Hugoniot pressure) is given by equation (1); the pressure of the steady flow (stagnation pressure) is calculated according to Bernoulli and is given by equation (2) [6]:

Hugoniot pressure:

$$P_{shock} = \rho_0 \, v_{shock} v_{impact} \quad (1)$$

Stagnation pressure:

$$P_{stagnation} = \frac{1}{2} \rho_0 \, v^2{}_{impact} \quad (2)$$

Analytically, those two pressures are important since the Hugoniot pressure gives the maximum possible value for the impact and the stagnation pressure gives the expected reading when the flow stabilizes. It is also important to realize that the pressure is independent of the size of the projectile since the mass is not a variable in the pressure equation. So while the force and energy of a larger projectile will cause more damage, the pressure results are the same for a bird of different weight. The values of the variables needed to calculate the stagnation pressure are easily available. On the other hand, the Hugoniot pressure depends on the impact velocity and the shock velocity, which itself also depends on the impact velocity. The information required to calculate the pressures are found in Wilbeck [7].

As can be seen in Equations (1) and (2), the bird velocity is closely related to the Hugoniot pressure and stagnation pressure formed on the plate. The angle of impact is a parameter that affects the bird velocity in the normal direction of the plate. All in all, bird velocity and impact angle are two main parameters affecting the Hugonoit pressure. Therefore, this study will examine the pressure distribution over the target as a result of bird strikes at different velocities and different impact angles.

3. Smoothed Particle Hydrodynamics (SPH) Bird Model

When the studies in the literature are investigated, the most commonly used bird model is SPH (the Smooth Particles Hydrodynamics Model), because it gives closer results to experimental data than other analysis methods [9-13].

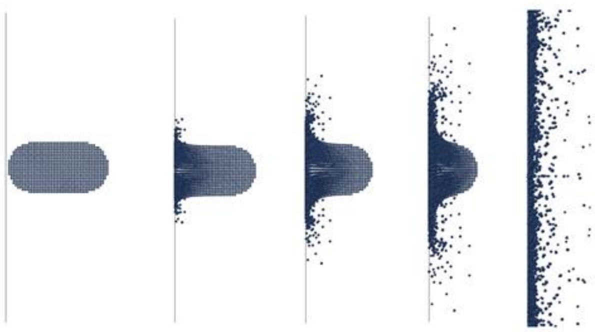

Fig. 4. Deformation of the SPH bird model

Compared to the conventional solid Lagrangian mesh, where the explicit time step decreases significantly with element deformation, the time step is constant for the SPH model. However, a sufficient particle density is required in order to achieve accurate results, which may necessitate high memory resources and typically is a compromise between accuracy and required CPU time [8]. The stages of the bird striking modeled as SPH are shown in Figure 4. In this study, an artificial bird was modeled using 15013 SPH nodes. Since 1.8 kg bird is used, the weight of each node is 0.119896 gr.

In general, compared to the Eulerian model, the SPH method requires fewer elements, avoids the material interface problems associated with it and normally has a shorter solution time. The numerical robustness, compared to the conventional Lagrangian mesh with its mesh distortion problems, is very high [8].

Composite laminates possessing high in-plane strength and stiffness are rather sensitive to damage initiated by transverse impact loads that can cause dents or material penetration by the projectile. Depending on the impact energy determined by the projectile mass and velocity and the properties of laminate impact loading can result in considerable reduction in material strength under tension, compression, and shear.

4. The Verifying of the Bird Strike Simulations on the Composite Target

The bird strike analysis was carried out via Ls-Dyna Prepost and Ls-Dyna Manager in the current study. To accurately predict the response of an aircraft structure under impact loading, it is essential to have an accurate bird model [6]. In this reseach, the bird is modeled as a cylinder with two hemispherical ends, as shown in Figure 4. The ratio of the length to the diameter of the bird is selected to be 2:1. The weight of the bird is 1.8 kg according to EASA CS-25.631 and FAA FAR-25.571-e-1 [4, 5]. The length of the bird is 228 mm and its diameter is 114 mm [14].

When the studies are examined in the literatüre [9-14], it is seen that many studies verify the model with the real bird strike test results in Wilbeck [7].

Convergence studies were performed determining the appropriate mesh size for obtaining accurate kinetic energy, Hugoniot pressure and stagnation pressure. As the appropriate mesh size, the mesh size of the composite plate is determined as 7.7 mm in the x and y direction and 8.47 mm in the z direction.

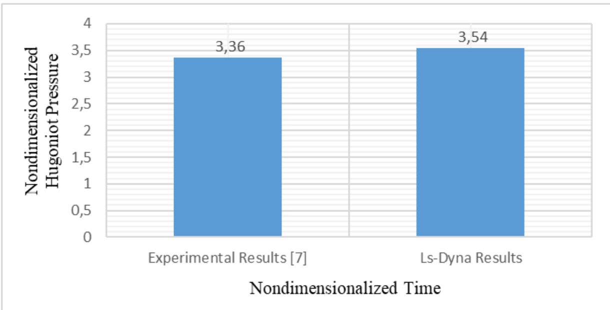

Fig.5. Comparison of real bird strike test results [7] with analysis results in terms of nondimensionalized Hugoniot pressure - nondimensionalized time.

The real bird was impacted perpendicularly at 116 m/s in the verification study as in actual test conditions. Typical pressure histories recorded at the center of impact for real bird strike are given in Figure 5 & 6. The obtained pressure values were divided by $P = {}^{1}/_{2}\rho v^2$ and the time was divided by $T_s = {}^{l}/_{v}$ (l: bird's length, ρ: bird's density, v: bird's velocity). The experimental [7] and analysis results of normalized Hugoniot pressure value is 3.36 and 3.54, respectively (The difference is 5.36%). The value of the normalized Hugoniot pressure is consistent with the value obtained from the experimental results [7], as clearly demonstrated in Fig. 5.

The normalized stagnation pressure value obtained from this study and experimental results [7] is 0.67 and 0.83, respectively. The difference between the simulation and the experiment of bird strike is 19.28%. This difference arises from the differences between tests and experiments.

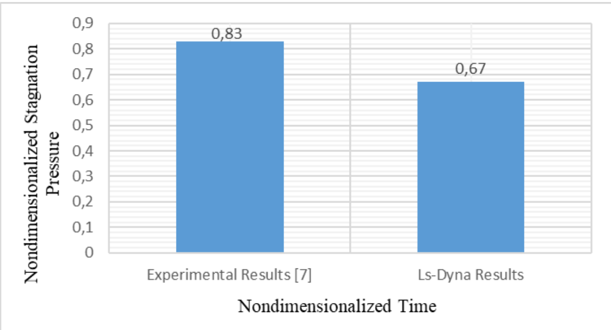

Fig. 6. Comparison of real bird strike test results [7] with analysis results in terms of nondimensionalized stagnation pressure - nondimensionalized time.

The analyzes have also been verified by comparing the kinetic energies. At the start, the analyses of bird strike were performed perpendicularly in different bird velocities. Bird's kinetic energy analysis results for bird velocity 116 m/s, 134 m/s and 152 m/s are 12100 J, 16200 J and 20800 J, respectively (Table 2). As expected, the kinetic energy of the bird increases as the velocity of bird increases. From the Table 2, it can be seen that the error percentage between the theoretical kinetic energy and Ls-Dyna result is about 0.086%, 0.244% and 0.031% respectively. This result shows that the bird strike model has a high predictive capability, and the bird strike model can replace the real bird strike tests.

Table 2. Comparison of the simulation with the theoretical kinetic energy (V_b: bird velocity [m/s])

V_b [m/s]	Simulation [J]	Theoretic [J]	Error (%)
116	12100	12110.40	0.086
134	16200	16160.40	0.244
152	20800	20793.60	0.031

Table 3. The properties of T700/M21 carbon fiber epoxy prepreg material [13]

Mechanical Constants (Symbols)	Values
Density (ρ)	1600 kg/m^3
Young's Modulus (E_A)	130 e+9 Pa
Young's Modulus (E_B)	7.7 e+9 Pa
Young's Modulus (E_C)	7.7 e+9 Pa
Poisson's Ratio (ν_{BA})	0.0195
Shear Modulus (G_{AB})	4.8 e+9 Pa
Shear Modulus (G_{BC})	4.8 e+9 Pa
Shear Modulus (G_{CA})	4.8 e+9 Pa
Ultimate Tensile Stress (X_T)	2080 e+6 Pa
Ultimate Tensile Stress (Y_T)	60 e+6 Pa
Ultimate Compressive Stress (X_C)	1100 e+6 Pa
Ultimate Compressive Stress (Y_C)	180 e+6 Pa
Ultimate Shear Stress (S_C)	110 e+6 Pa
Failure Criterion ($CRIT$) / Tsai-Wu	55

For applying the boundary conditions of the target during analysis, the edges of the target are fixed. The properties of T700/M21 carbon fiber material used in the analyses are given in Table 3.

In this study, the composite target is 36 ply and its stacking sequence is $[0_2/45_2/90_2/\text{-}45_2/0_2/\text{-}45_2/0_2/45_2/0_2]_s$. Such a quasi-isotropic ply orientation simulates the properties of an isotropic material. It is therefore advisable to build a symmetrical and balanced laminate to minimize any residual thermal stresses induced during resin curing.

5. Response Surface Design

In studies in the literature [15-21], typically, response surface methodology (RSM) is used to optimize the process parameters in casting, welding and machinability studies of composite materials. In this study, different from the studies in the literature, the significant variables which are bird velocity and impact angle are examined using response surface methodology (RSM) based on central composite design (CCD). Response surface design is two types: Central Composite designs and Box-Behnken designs.

Central composite design method

Compared to other DOE methods, the Central Composite Design method is the most suitable method for this problem. Central Composite Design method minimises the number of experiments for a specific number of factors and its levels. Experiments are conducted as per the experimental design matrix and the output responses are recorded for analysis. The process parameters which significantly influence the response are identified using analysis of variance. Regression equations are used to predict the response for the given process parameters and its levels. Response surface plots are used to understand the effect of process parameters on response. Finally, the process parameters are optimised using desirability approach of response surface methodology and confirmed by conducting confirmation tests [15]. Central composite designs are a factorial or fractional factorial design with center points, augmented with a group of axial points that allow the curvature to be predicted. Central composite designs are especially useful in sequential experiments because that can be build on previous factorial experiments by adding axial and center points [22]. After conducting bird strike analysis in two different parameters in Ls-Dyna, the Central Composite Design method was applied.

The Central Composite Design method was applied after 12 different bird strike analysis was done in Ls-Dyna, with 2 different design parameters, 3 levels for bird speed (116 m/s, 134 m/s and 152 m/s) and 4 levels (0^0, 30^0, 45^0 and 60^0) for impact angle. Twelve different test were prepared, these analyzes were analyzed in Minitab with the Central Composite Design method. As a result, four different analyzes were obtained from Minitab. The total number of analyzes which is performed is sixteen in different impact angles and bird velocities. These sixteen different analyzes were conducted at Ls-Dyna. Analysis results are presented in Table 4 and Table 5. The z-direction deformation of the plate and the pressure values in the center of the plate depending on the bird velocity and the angle of impact are shown in Table 4. Table 5 presents the kinetic energy of plate, the plate of internal energy and the bird of internal energy values from the bird strike analysis results.

Table 4. Z displacement, penetration and pressure results in Ls-Dyna

Input		Output		
Bird Velocity [m/s]	**Impact Angle**	**z disp. [mm]**	**Penetration**	**Pressure in the Center of Plate [Mpa]**
116	0	180.00	yes	314
116	30	33.30	no	298
116	45	12.82	no	291
116	60	5.09	no	298
134	0	223.00	no	319
134	30	153.05	yes	318
134	45	15.69	no	327
134	60	5.60	no	186
152	0	254.70	yes	207
152	30	239.93	yes	315
152	45	100.76	yes	291
152	60	6.27	no	299
108.544	30	25.27	no	305
134	-124.264	242.78	yes	310
134	724.264	1.46	no	155
159.456	30	281.59	yes	316

Table 5. Kinetic energy and inertial energy in bird strike analysis

Input		Output		
Bird Velocity [m/s]	**Impact Angle**	**The Kinetic Energy of Plate [J]**	**The Plate of Internal Energy [J]**	**The Bird of Internal Energy [J]**
116	0	1310	7890	444
116	30	708	2680	370
116	45	471	1380	276
116	60	220	668	147
134	0	2520	10700	509
134	30	1910	10200	631
134	45	701	2290	354
134	60	346	968	196
152	0	3360	12000	836
152	30	3100	10100	476
152	45	872	8300	573
152	60	504	1400	256
108.544	30	594	1870	326
134	-124.264	2360	10800	455
134	724.264	112	312	80.5
159.456	30	3910	16000	699

6. Result and Discussion

6.1. Internal energy of plate

The accuracy of the bird strike model in this study by using three statistical parameters. These parameters are the coefficient of the multiple determination R-sq, root mean squared error (RMSE) and then adjusted coefficient of determination R-sq (adj), respectively. The R-sq and R-sq (adj) values of around 80% indicate that the model fits well with the bird strike model in Ls-Dyna (Table 6).

Table 6. Plate's internal energy DOE model summary

S	R-sq	R-sq(adj)	R-sq(pred)
2361.75	85.87%	78.80%	52.54%

Regression Equations (4) and (5) are obtained from Minitab (V_b: Bird Velocity [m/s], α: Impact Angle [deg]). The internal energy of the plate is min 312 J, max 16000 J from Equation (4).

$$Internal\ Energy\ Plate\ [J] = -2702\ -\ 32\ V_b + 113\ \alpha$$

$$+\ 0{,}96\ {V_b}^2 -\ 1{,}33\ \alpha^2 - 1{,}33\ V_b * \alpha \qquad (4)$$

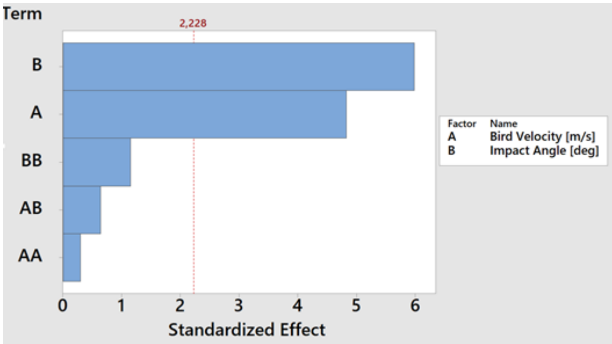

Fig. 7. Pareto chart of the standardized effects (response is the plate of kinetic energy and internal energy for $\alpha = 0.05$)

Information about the effect of each input parameter on bird strike analysis results is provided in the Figure 7. According to Figure 7, at 95% confidence interval, it is the angle of impact that most affects the kinetic energy and internal energy results.

Kinetic energy, internal energy and z displacement are output in bird strike analysis. Figure 8 shows internal energy predicted from the analysis results as the bird velocity and the angle of impact change.

There are two factors: bird velocity and impact angle. The range of bird velocity in the analysis is 108,544 m/s and 159,456 m/s. The range of the impact angle is -12.4264^0 and 72.4264^0 degrees. As we consider the values in the data set, while the bird velocity is 159.456 m/s and the angle of impact is -12.4264^0, the internal energy of the plate is at the maximum value and is 17607.9 J.

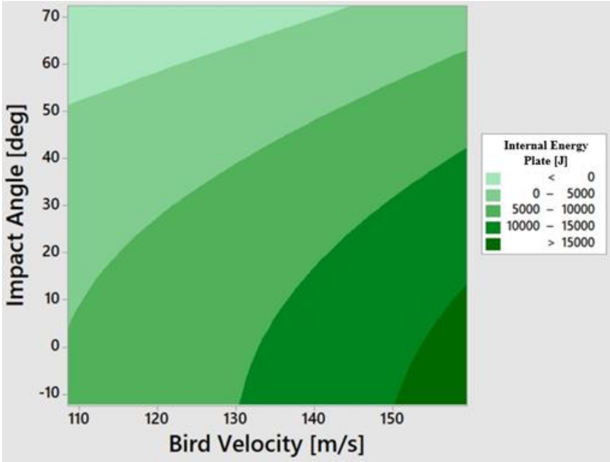

Fig. 8. Contour plot of internal energy

6.2. Kinetic energy of plate

The bird of theoretical kinetic energy is calculated $0.5 * m * {V_b}^2$. The min. kinetic energy value formed on the plate is 112 J, and the max. value is 3910 J from Equation (5).

$$K.E.Plate\ [J] = 2239 - 77\ V_b + 117{,}0\ \alpha$$

$$+\ 0{,}578\ {V_b}^2 -\ 0{,}271\ \alpha^2 -\ 0{,}999\ V_b * \alpha \qquad (5)$$

The R-sq and R-sq (adj) values of around 80% indicate that the model fits well with the bird strike model in Ls-Dyna (Table 7). It can be concluded that the numerical results of kinetic energy also perfectly matched with the theoretical bird strike analysis results (Table 7).

Table 7. Plate's kinetic energy DOE model summary

S	R-sq	R-sq(adj)	R-sq(pred)
511.532	88.71%	83.07%	67.92%

Figure 9 presents kinetic energy predicted from the analysis results depending on bird velocity and impact angle. According to this figure, the most damage occurs on the composite material at high bird velocity and when the bird is impacted perpendicularly.

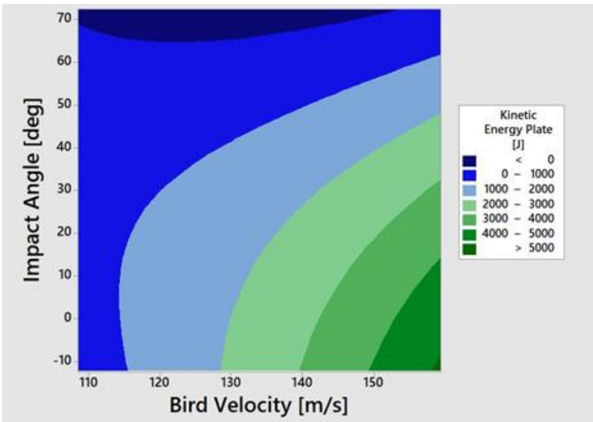

Fig. 9. Contour plot of kinetic energy

7. Conclusion

In this study, the damage caused by the bird strike problem, which is one of the most risky issues for aviation, on composite materials and energy transfer issues were examined.

A bird strike model requires high computational power for model preparation and nonlinear explicit analysis because of composite materials, contact definitions and other complex analysis parameters.

Investigation of the effects of bird parameters on a composite target provides a clearer definition of the strength limits and energy transfer of composite materials exposed to bird strikes.

Firstly, the numerical results were compared with theoretical and experimental studies in the literature and verified as a result of iterations. Secondly, the Ls-Dyna analysis was expanded by considering the design variables. The bird velocity and impact angle were considered as design variables.

Central Composite Design (CCD) method was very effective in predicting analysis results of the composite target which was subjected to bird strike. Investigating the effects of design parameters on bird strike is a costly and time consuming practice. In this study, the result values were estimated using the Central Composite Design method in order to get a faster response, and with the regression equations obtained as a result of the analysis, the effect of which parameter on the bird strike event was found. The good correlation between the experimental data and the Ls-Dyna simulations confirms that the properties used for the bird in the numerical simulations are appropriate. In future studies, other analysis results can be estimated using the same methodology. Thus, analysis results can be predicted with a certain accuracy in a shorter time via scholastic methods.

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